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EVALUATION AND COMPARISON OF THREE SPACE SUIT ASSEMBLIES

by R. L. Jones

Manned Spacecraft Center
Houston, Texas

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ABSTRACT

This report describes in detail the program by which the MSC evaluates the performance of space suits. The testing quantifies various aspects of suit design, function, operation, and man-suit-system interface. The technique evaluates the suits with a basic rationale emphasizing mission requirements, and the procedures are structured in such a manner as to maximize objectivity.

Test results are presented on the evaluation of three different space suits. These results indicate the relative position of each suit in each test and the differences between suits. By a collation of these data, the various interested but not specialized technical personnel can obtain data which reveal the state of technology of space suit design and development. These data can be used by engineers in vehicle design to determine the impact on detail design of the space-suited operator. In this application of these data, the best performance in any single test of any of the three suits should be used as minimum design criteria.

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ERRATA

NASA Technical Note TN D-3482

By R. L. Jones, Ph. D.

FOREWORD

Coauthors and directors of subtests for the test program were R. H. Hester, J. H. O'Kane, E. L. Michel, G. M. Burnett, J. B. Slight, W. D. Salyer, J. F. Rayfield, D. E. Kirkpatrick, and G. A. Eldred. Assisting the test team were J. Nuttal, G. Post, G. West, J. Lewis, B. Covey, Major D. Fulgham (USAF), P. Vasquez, R. Drexel, J. Ottinger, W. Blunck, J. Dobbs, M. Ferrill, H. Jones, and R. Sandridge. Astronaut M. Collins served as test subject and as a member of the test team, and Jack D. Mays served as the second subject. The test team is grateful for help received from the Aviation Medical Acceleration Laboratory, Naval Air Development Center, Johnsville, Pennsylvania. Special appreciation is also given Dr. S. Schwartz, Dr. R. Del Vecchio, and supporting personnel at Grumman Aircraft Engineering Corporation, Bethpage, Long Island, New York, for their role in the test program.

The space suit evaluation presented in this report represents a summary of pertinent data and omits minute detail and the specific ratings assigned to the various space suits.

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EVALUATION AND COMPARISON OF THREE SPACE SUIT ASSEMBLIES

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SUMMARY

Results are presented from a comprehensive test program conducted to evaluate and compare three space suit assemblies. The testing program included an evaluation of various aspects of suit design, function, operation, and man-suit-system interface. By broad classification, the tests are described as operational functions test, engineering test, basic functions test, comfort evaluation test, and field maintenance test. Subtests were conducted under each of these classifications. Test conditions were controlled to present testing situations identical for each suit, to evaluate the suits with a basic rationale emphasizing mission requirements, and to structure test procedures in such a manner as to maximize objectivity. A scoring system was developed so that test results would indicate the relative position of each suit in each test and also indicate the magnitude of differences between suits. It is recommended that the test results serve as guidelines to enhance suit development. It is also suggested that the test procedures be refined into an analytical tool for use in competitive evaluation, in development design, and in management decision making.

INTRODUCTION

This report presents the test results obtained from a controlled evaluation and comparison of three space suit assemblies. The evaluation and comparison were made with mission suitability as the frame of reference; therefore, major emphasis was placed upon evaluation of those basic characteristics of the suits which reflect the underlying rationale and philosophy of the suit design. Predominant concern was with those aspects of basic suit configuration which significantly affect suit-mission interface. Refined and detailed engineering testing of all suit components, taken singly and in interaction, was not appropriate at this time because of restrictions placed upon time, and because of quality control requirements, test philosophy, and objectives. Also numerous component changes can be effected at a later stage of development and production, according to imposed specifications.

The primary purpose of this test program was to perform an objective comparison of the suits by establishing a series of test tasks consistent with the basic test philosophy. The intention was to derive meaningful data which would yield objective criteria for basing judgments concerning the relative merits of the three space suits. The suits were evaluated under test conditions which were identical for each suit, and objective data were utilized in a comparison of the test suits. Since the basic orientation of this test program was aimed toward acquisition of data relative to operational mission aspects, operational tests were given priority in scheduling.

SYMBOLS

g acceleration due to gravity, 32.2 ft/sec^2

m mass flow rate, lb/min

p pressure, lb/ft^2, absolute

Δp pressure drop, inches of H_20

R gas constant = 48.3 ft-lb/lb-°R for 0_2

T temperature, °R

V volume flow, cu ft/min

ρ gas density, lb/cu ft

Subscripts:

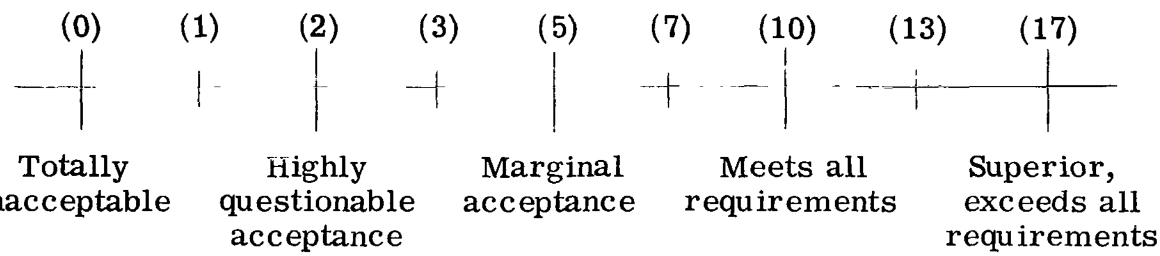
a altitude conditions (design point)

s sea level conditions

SCORING APPROACH

In most cases, the various subtests yield objective data. In many cases, however, the evaluation of suit performance tends to be quite subjective, thus tending to add a confusing variable to the comparison analysis. An added factor to be considered is that these suits might be expected to meet minimum values of acceptance, since all were built with the same basic frame of reference. Consequently, it was necessary to structure an evaluation scheme which presents a continuum of the performance or attribute under consideration. Along this continuum the function can be rated subjectively or located with respect to objectively derived data. Such a scheme permits consideration of the magnitude of the differences between the suits.

In order to account for these factors, a nine-point scale was utilized for summarizing suit performance on the test variables. (See appendix A for forms used by rating team and test subject.) Where objective data were derived, the data were converted to the scale; and where judgments comprised the evaluation system, the variable was subjectively rated along the scale by a team of judges. The scale is as follows:



For each subtest, a director and a rating team were responsible for the ratings and for the conversion of objective data to the rating scheme applying for the particular area. Also, the subject wearing the suit rated the suit performance on each subtest and evaluated suit comfort. A final, composite evaluation for each suit was made on the basis of all subtest results.

A system of weights was used to establish the relative importance of various tests and subtests. As shown in table I, the operational functions tests accounted for 43 percent of the total score, engineering tests for 33 percent, basic functions for 17 percent, and comfort for 7 percent. Subtests were also weighted (table I) according to their relative importance in the test program. In this case, weights were assigned by a committee of five representatives (of NASA Manned Spacecraft Center) who were experienced in suit development and suit testing programs.

TABLE I. - TOTAL TEST SCORE AS RELATED TO WEIGHTING FACTORS OF TESTS AND SUBTESTS

Total Score

Operational functions	W[a] 43 percent
	W
1 Reach in CM[b]	5
2 Vision in CM	5
3 Reach in LEM[c]	5
4 Vision in LEM	5
5 Suit adjustments	10
6 CM and LEM operational mobility	10
7 Physiological tests	6

Engineering test	W[a] 33 percent
	W
1 Pressure drop	4
2 Leakage	4
3 Helmet design	7
4 Component functions	13
5 Dimensions	5
6 Weight	3
7 Inspection	5
8 Proof pressure	2
9 Centrifuge tests	4

Field maintenance evaluation (not included in scoring)

Basic functions	W[a] 17 percent
	W
1 Mobility, general and ranges of motion	6
2 Eye-heart angle and X-ray study	3
3 Maximum visual field	5
4 Hand dexterity	4
5 Functional reach	4

Comfort	W[a] 7 percent

[a]W = Weighting factor.

[b]CM = Command module.

[c]LEM = Lunar excursion module.

SUIT DESCRIPTION

The suits submitted for evaluation (shown in the vented condition in figures 1 through 3 and in the pressurized condition in figures 4 through 6) were to meet the following descriptive requirements.

The pressure garment assembly (PGA) was to consist of helmet, torso, gloves, and boot assemblies, and was to integrate with a constant wear garment, a liquid cooled garment, and an overall thermal protective garment, all of which were Government-furnished equipment (GFE). The PGA was to be a flexible, anthropomorphous pressure vessel completely enclosing the crewman and consisting of a limb and torso garment with integral boots and with helmet and gloves of a separable nature.

The helmet was to be a "bubble" type with a fixed eyepiece and an integrated sealing neck ring concept. It was to provide communication facilities, access for pressurized feeding, sound and impact attenuation, ventilation, and a quick connect/disconnect capability. The gloves, which were to be furnished by the contractor, were to be hand-shaped, flexible, molded, envelope types.

An extravehicular light attenuation system was to be provided, and a defogging capability was to be built into the system.

The entry was to be simplified. The torso was to maintain as closely as possible the dimensions established for Apollo intravehicular application; that is, a 24-inch shoulder and elbow breadth.

Wrist, gas, and water disconnects, relief valves, and pressure gages were either Government-furnished or the equivalent for all suits. The portable life-support systems (PLSS) to be used were furnished to all contractors upon request so that their adequate integration with the suits would be assured.

Pressure drop limitations for the ventilation and the total-suit systems as well as permissible leakage rates were stipulated by the Government. Overall weight limits were also imposed.

The constant wear undergarment had to meet requirements for the incorporation of GFE bioinstrumentation equipment, and had to be capable of being worn beneath the PGA. The liquid cooled garment was GFE to the contractor. It too was required to be worn alone and comfortably beneath the PGA. Fittings for liquid flow lines were GFE, as were the thermal garments. Minor modifications were acceptable in all GFE, however, so long as the basic function and integrity of the equipment were unimpaired.

Figure 1. - Space suit A, vented.

Figure 2. - Space suit C, vented.

Figure 3. - Space suit B, vented.

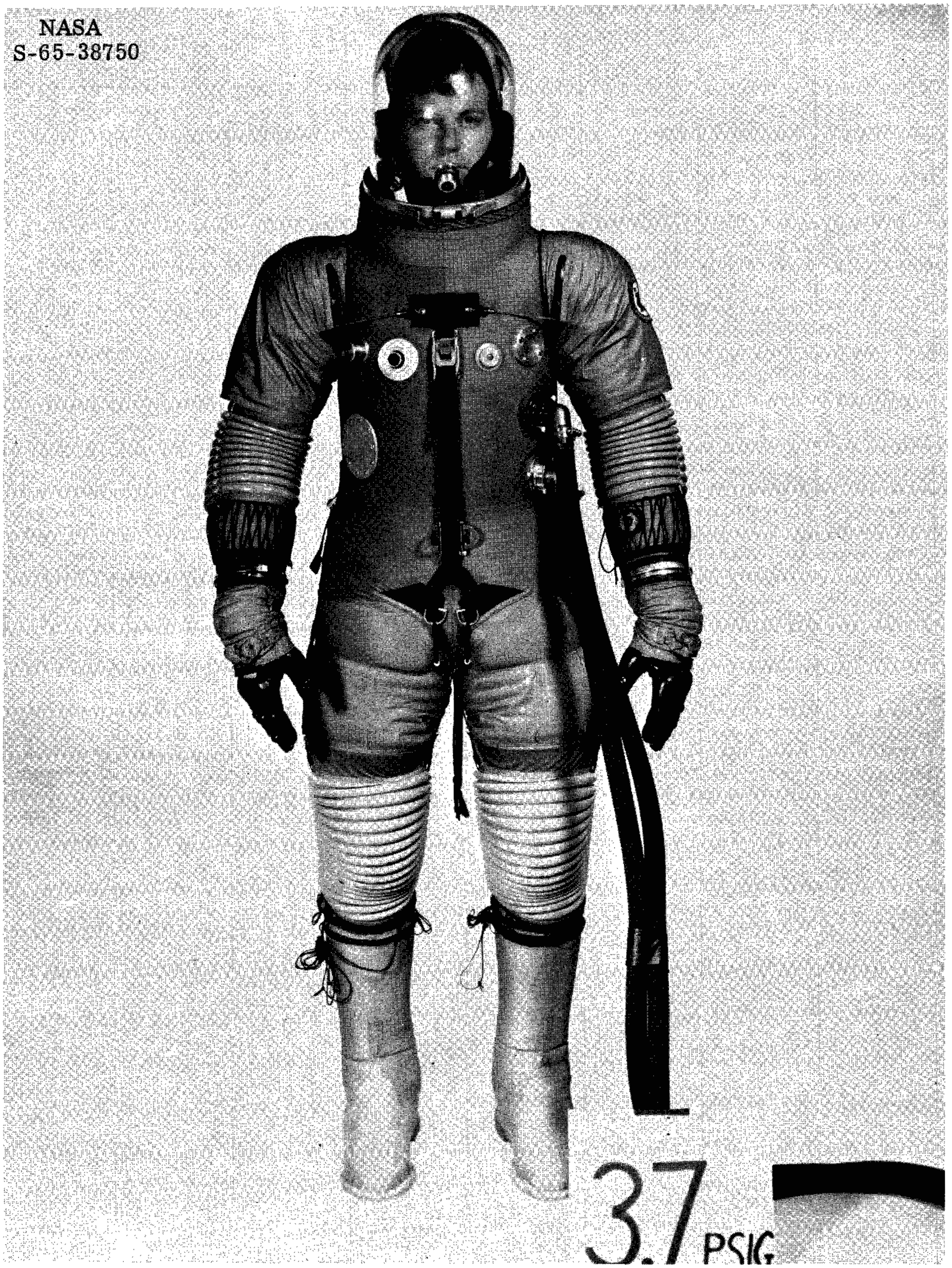


Figure 4. - Space suit A, pressurized.

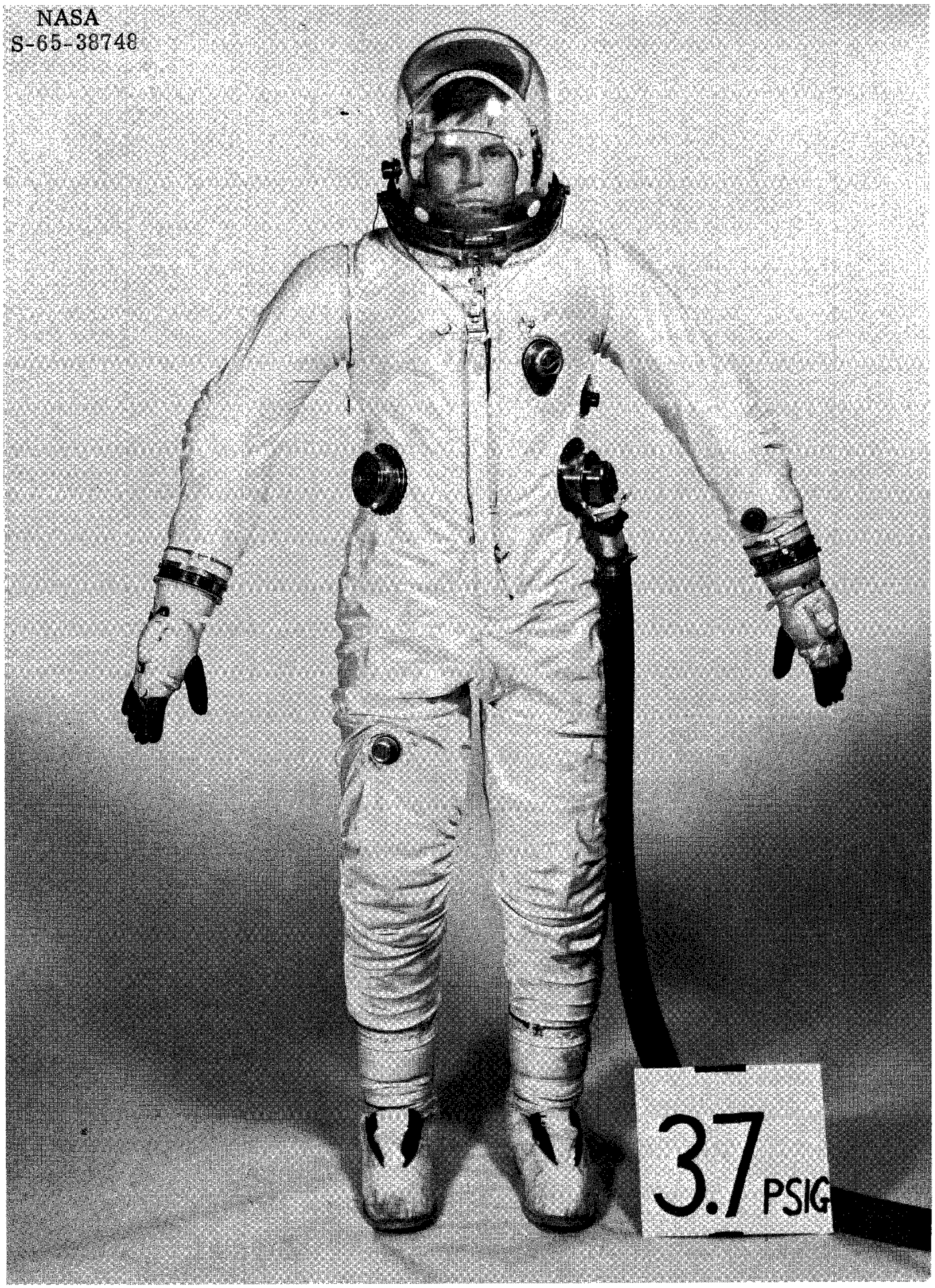


Figure 5. - Space suit C, pressurized.

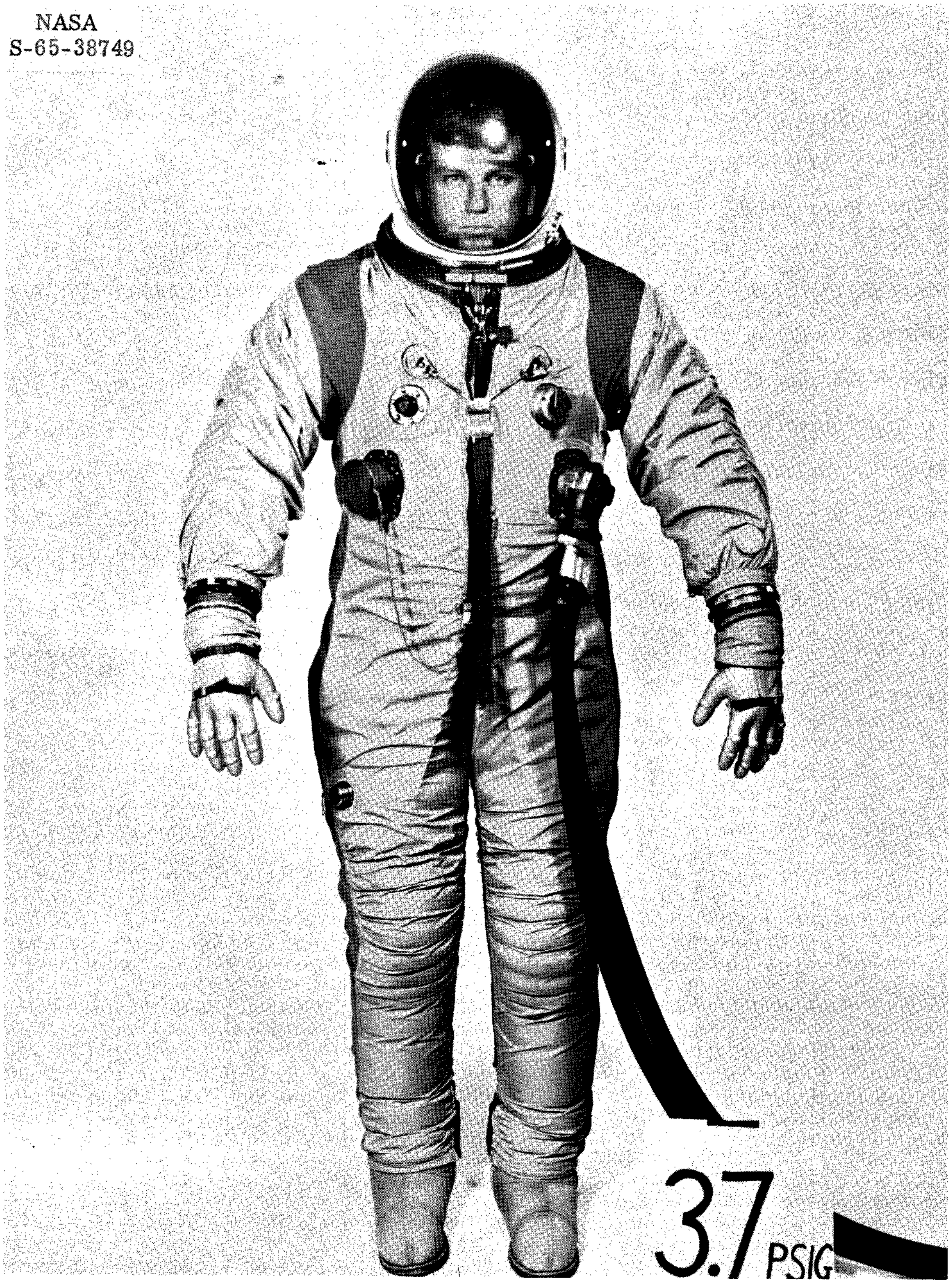


Figure 6. - Space suit B, pressurized.

Sizing of suits was limited to astronaut M. Collins' dimensions. Mobility, comfort, and donning requirements, which were supplied in detail, were those established generally for the Apollo space suit.

GENERAL PROCEDURES

A test conductor was responsible for supervision and coordination of the overall test program. He was assisted by nine subtest directors who were responsible for performing and evaluating all subtests according to the study design and philosophy. An astronaut served as the primary subject wearing the space suits, and another NASA representative served as a backup subject. All aspects of suit fitting and pressurization monitoring were the responsibility of highly trained space suit technicians of the Crew Systems Division.

Technical representatives from each of the three space suit contractors observed their respective suits throughout the test program.

In order to proceed in a timely and orderly manner, certain guidelines relative to maintenance were established at the outset of the test program. These guidelines concerned criteria about the nature of suit failures, the time to be allowed for repair, and the test result impact. While these guidelines included a point-loss system for extensive repair time, it should be noted that tests which were missed because of suit failure or because of repair delays were rescheduled and subsequently accomplished. The only test which was not made up was the centrifuge pressure-point test for suit A, and this test could not be rescheduled due to coordination and scheduling difficulties within the time period allowed. Consequently, the only zero included in the test scores was that for the suit A centrifuge test.

To verify that the internal suit pressure was identical for each suit and each test, a redundant sensor was installed through the helmet feed port, and readings were made on suit pressure gages. Conditions were carefully controlled throughout the entire test program to insure that all suits were tested under identical conditions. Whenever possible, conditions were structured to simulate mission situations to the maximum degree possible under the exigencies of the program.

OPERATIONAL FUNCTIONS TEST

The operational functions test consisting of seven subtests, accounted for 43 percent of the total score for each space suit. Table II gives the relative weights of the subtests, their objectives, and the equipment necessary for carrying out the subtests.

Operational Reach in the Command Module

Wearing the constant wear garment (CWG), the test subject was suited and appropriately restrained in the command module (CM) couch. Insert pads were worn in the helmet, and the suit was vented (0. 18 psig) and pressurized (3. 7 psig) during the reach measurements. The test subject described the arc of his functional-operational reach on the panels, and these limits were drawn directly on paper taped over the panels. For panel layout, see figure 7. In both the vented and pressurized conditions, the reach of suit A was superior to that of suits B and C. This was true for all panel areas.

For the vented condition, the arc covered by suit A right hand was slightly greater (about $\frac{1}{2}$ in.) than that covered by suit B right hand, and more than 2 inches greater than that covered by suit C right hand. Arcs for the pressurized right hand were almost exactly the same for all three suits. For the vented condition, the arc covered by suit A left hand was approximately 1 inch greater than that covered by suit C left hand, and was 5 inches greater than that covered by suit B left hand. For the pressurized left hand, the arc covered by suit A was approximately 2 inches greater than that covered by suit C, and was 4 inches greater than that covered by suit B.

As for decrements to the vented operational-reach arc brought about by pressurization to 3. 7 psig (pounds per square inch gage), there was essentially no loss to the suit A right-hand arc at 3. 7 psig as compared with the vented condition right-hand arc; and there was a 7-inch loss in arc for the left hand at 3. 7 psig. For suit C, there was a $1\frac{1}{2}$-inch loss for the right hand and a $9\frac{1}{2}$- inch loss for the left hand. For suit B, there was a 2-inch loss for the right hand and a 6-inch loss for the left hand.

On the side panels, all three suits could reach panel 26 satisfactorily in both the vented and 3. 7 psig conditions. On panel 25, the suit A left-hand reach (while vented) exceeded that at suit C by more than 2 inches, and exceeded that of suit B by more than 3 inches. For the pressurized condition, the suit A left-hand reach exceeded that of suit B by 4 inches and that of suit C

TABLE II. - SUBTESTS OF THE OPERATIONAL FUNCTIONS TEST

Subtests	Objectives	Necessary equipment
Subtest 1 (weight 5); reach in CM	To establish the limits of operational-functional reach for the suited, restrained subject in the CM couch.	CM mockup and appropriate pressurization and communication equipment.
Subtest 2 (weight 5); vision in CM	To obtain a measure of the subject's visual field in the CM; for the pressurized, restrained condition and the vented, restrained condition.	CM mockup and appropriate pressurization and communication equipment.
Subtest 3 (weight 5); reach in LEM	To establish the operational-reach limits for the suited, pressurized subject in the LEM.	LEM mockup and appropriate pressurization and communication equipment.
Subtest 4 (weight 5); vision in LEM	To determine the suited, pressurized subject's operational field of vision in the LEM.	LEM mockup and appropriate pressurization and communication equipment.
Subtest 5 (weight 10); suit adjustments	To analyze the capability of the subject to make the suit adjustments necessary for mission success, and to determine the relative efficiency of the subject to carry out these functions.	None
Subtest 6 (weight 10); CM and LEM operational mobility	To establish the limits of operational mobility relative to the subject's capability to carry out various significant mission activities in the CM and LEM including; LEM ingress/egress and access to the LEM interior in the pressurized state, access to the lower-equipment bay in the CM, and the subject's capability to adequately operate the attitude controller while pressurized and restrained in the CM left couch.	LEM and CM mockups and appropriate pressurization and communication equipment.
Subtest 7 (weight 6); physiological tests	To evaluate and compare the following areas; metabolic cost, CO_2 washout characteristics, and ventilation adequacy.	Treadmill and equipment for monitoring CO_2 concentration.

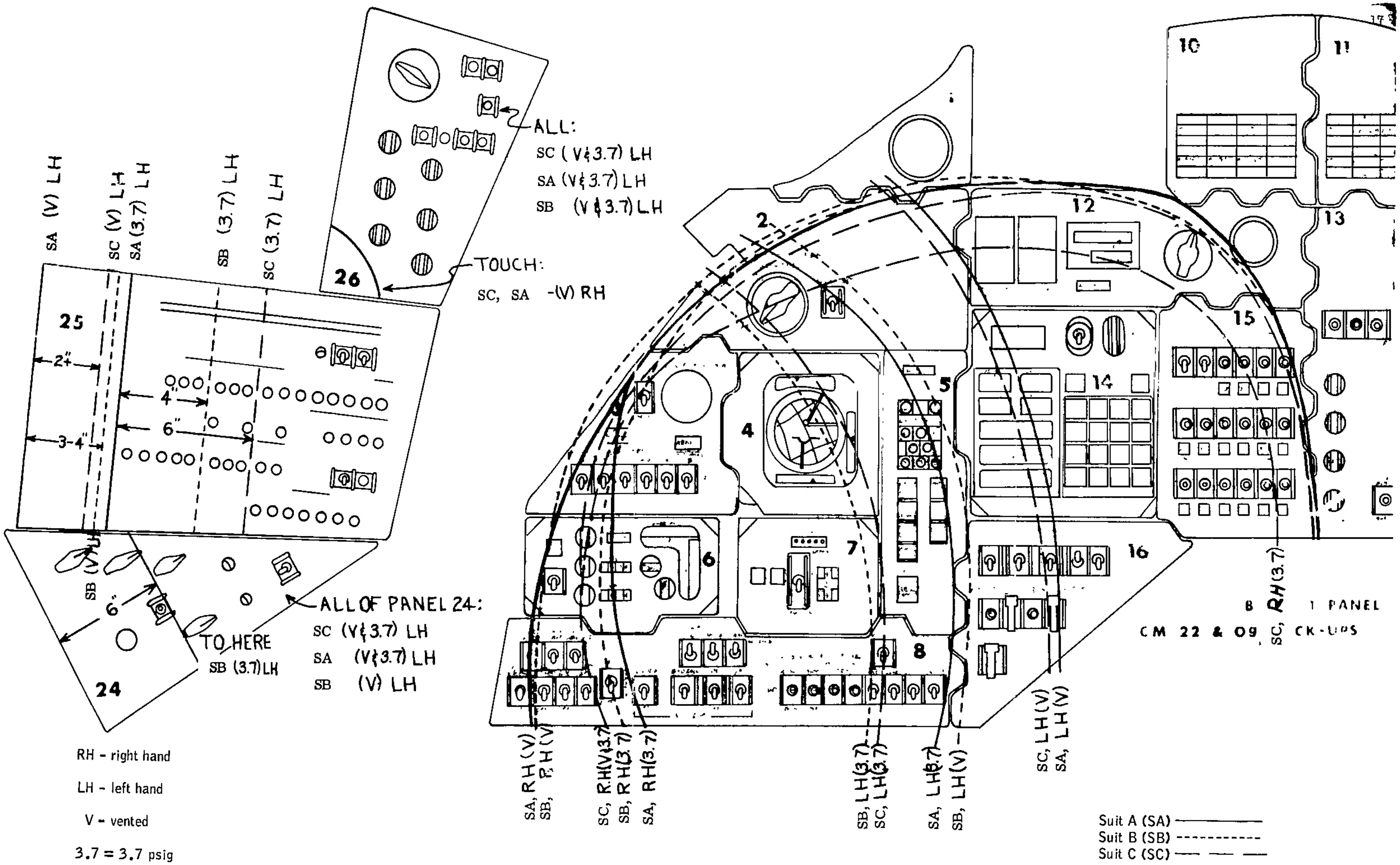


Figure 7. - Command module panel showing operational-reach arcs.

by 6 inches. On panel 24, suits A and C left hand were able to reach all controls during both the vented and pressurized conditions, while suit B was able to reach all controls only during the vented condition, and was not able to operate in the farthest 6 inches of the panel.

With the left hand pressurized, the subject in suit A was able to reach the first cabin-air-pressure regulator, but not the second. He was also able to reach the bulkhead directly overhead and around to the left; and, at 3.7 psig, he could reach the left and overhead windows. The lower left-hand area was completely inaccessible for suits B and C, and the overhead reach was also significantly less for these two suits.

As for ease of movement, the subject noted that pressurization seemed to enhance upward mobility in suit A, and there was virtually no torque for these movements. He also noted that he definitely felt the shoulder bearing operate in suit C and that the combination of rings appeared to add to mobility and reduce torque, thus reducing, if not eliminating, the need to "fight the link net." According to the subject's appraisal of the effort involved in achieving operational reach, the greatest amount of effort required for movements was with suit B. In commenting on pressure points, the subject noted a pressure point behind each knee when pressurized in suit C. He was able to relieve this condition by stretching out his legs. In suits A and B, the subject noted pressure points on the shoulders. In suit A, the zipper created a pressure point along the lower back, and there was an area of pressure along the inner thigh and groin area.

Visual Field in the Command Module

Wearing the CWG, the test subject was appropriately restrained in the left couch of the CM. The head was appropriately positioned with the insert pad in the helmet. With the helmet in a fixed position, but with the head and eyes moving, the test subject determined the operational-functional field of view. This field of view was defined as the extent to which the test subject could make appropriate responses to visual stimuli in portions of the CM and on panels of controls and displays. The test subject made a verbal report on the visual field in terms of his operational-functional field of view. Using these data, each suit was rated along the nine-point scale. Tests were conducted for both the vented and pressurized conditions; and under both conditions, the visual field for suit A was superior to that for the other two space suits.

In suit A, the subject was able to see all control-display panels, to see panels across the CM in the area of the right couch, to see out the side windows and docking windows, and to see forward and downward (to the upper chest and neck areas). Vision from within suit C was somewhat less than from suit A. This vision restriction in suit C was brought about because the insert head pad and the communications cap rubbed together, causing the communications cap to slide forward on the forehead and thus limit the upward and lateral vision. For suit C, both forward and downward vision were identical to that obtained in suit A. Vision in suit B was more restricted than in either of the other two suits. From suit B, the vision restrictions were mainly in the downward and lateral areas, and the subject was not able to see areas directly to his side as he was in the other two suits. Concerning suit B, one significant factor was that the communications cap constantly slipped down and rode directly over the subject's eyes, forcing him to make extensive head maneuvers within the helmet.

Operational Reach in the Lunar Excursion Module

Wearing the liquid cooled garment (LCG), the test subject was suited in the pressure garment assembly (PGA) and was pressurized to 3.7 psig. The subject occupied the left-hand station position in the lunar excursion module (LEM), and his foot position was marked so that the same position could be taken for tests in each space suit. A paper overlay was placed over the control-display panels, thus permitting the test subject to mark the arc of his reach. Without moving from the specified foot position and while maintaining one arm on the appropriate armrest, he traced the arc-of-reach on the paper overlay. Also, the test subject verbally described the field-of-reach as he simulated those movements he would perform while maintaining operational conditions. In addition, the test subject made a personal judgment concerning the capability of the suit to allow adequate operational reach for the conditions considered.

The functional arm reach of suit A was significantly greater than that of the other two suits. In suit A, the subject was able to reach across the center panel and sweep through an arc upward and to the left which was $4\frac{1}{2}$ inches greater than that of suit B and 7 inches greater than that of suit C. Directly to the right, the suit A reach was $1\frac{1}{2}$ inches greater than that of suit B and 4 inches greater than that of suit C. To the front and upward (toward the top of the panel), the reach of suit A was $1\frac{1}{2}$ inches greater than that of suit B and 5 inches greater than that of suit C.

Suit A had a definite advantage in reaching across the torso. The test subject was positioned in the left-hand station; but by reaching his left hand across the torso, he was able to sweep his hand through a 15-inch arc on the center panel. Neither of the other two suits had this capability.

In the vicinity of the side panels, the suit A reach of the left hand was significantly greater than for the other two suits. In this particular case, the test subject in suit A was able to reach well beyond the side panels and to the bulkhead directly behind him. This reach exceeded that of suit B by $9\frac{1}{2}$ inches and that of suit C by $11\frac{1}{2}$ inches.

Visual Field in the Lunar Excursion Module

Wearing the LCG, the test subject was suited in the PGA and was pressurized to 3.7 psig. The subject occupied the left-hand station position in the LEM, and his foot position was marked on the floor so that the same position could be taken for tests in each space suit. With the helmet in a fixed position, but with the head and eyes moving, the test subject made a verbal report on his visual field. Capability was also ascertained for sighting through the overhead docking window. In this particular case, the subject sighted through a reticle and held that position, thus simulating a docking effort. The test subject also made a judgment in terms of the capability of the suit to meet LEM visual operational requirements. The visual field available from suit C was superior to that from either of the other two suits because the insert pad was not a requisite condition and hence was not worn.

Wearing suit C, the test subject could see downward to about 1 foot in front of his feet. This downward vision was the same as for suit A and closer toward the feet than for suit B. Upward vision from suit C was better than from either of the other suits. For the upward vision, the test subject in suit C could see back about 6 inches from the front bulkhead intersection; vision from suit A was approximately the same, but vision from suit B included only the bulkhead intersection and no farther back. For suits A and C, lateral vision included the area to the right of the right-hand window, but vision in this area was restricted for suit B. (For suit B, lateral vision was restricted to the area up to the right-hand window.) For suits A and C, vision to the left included the left panels. For suit C, vision to the left exceeded the suit B vision by approximately 4 inches.

Vision from suit C was also superior in sighting through the overhead docking window. When wearing either suits A or C, the test subject could see about 4 inches aft of the docking window, and this distance was more than 2 inches farther back than for suit B. In addition, there was significantly less effort involved in sighting from within suit C. To permit optimum sighting efficiency, the reticle appears to be too far back and too far to the left on the docking window. It should be noted that the distance from the top of the helmet (pressurized, with extravehicular visors on) to the docking window was 3 inches for suit B and $3\frac{3}{4}$ inches for suit A.

Suit Adjustments

This subtest evaluated the three space suits according to a fixed set of tasks which were performed under conditions that were held constant. A final score for each suit was based on ratings assigned to each of the task functions. Table III shows a list of tasks, task conditions, and brief analyses of the results. When applicable, the task was timed, and this information was incorporated into the task rating system. Tables IV(a) and (b) show the performance time for various adjustment tests performed on the three space suits.

Final ratings indicated that suit A placed highest in the suit adjustment tests. Based on test results, the following conclusions were reached.

1. For all three suits, the suit entry is not adequate for the mission requirements due to difficulty of operation and excessive leakage.

2. Gloves for all three suits can be donned in approximately the same length of time.

3. The extravehicular visor of suit C was the only functionally acceptable visor assembly.

4. The tiedown of suit C was superior to the tiedowns of the other suits; however, the suit C tiedown should incorporate a positive lock.

5. In terms of making the connection, there were no operational differences between the gas connectors of the three suits.

6. The water connectors supplied by suits B and C required the same time and level of difficulty to operate.

7. The diverter valve of suit B was preferred over that of suit C because of its visible location, even though it had positions which were not functional.

8. If suit A increased the arc through which the "lock" and "open" indications are written, there would be no difficulty in using any one of the three wrist disconnect locking indicators.

TABLE III. - SUIT ADJUSTMENTS INCLUDING TASKS, CONDITIONS, AND ANALYSES

Tasks	Conditions	Analyses
Donning and doffing suit	Suit folded on the floor in front of subject; subject wearing CWG (task was timed)	Suit B was donned more rapidly than suit C, but it should be noted that the alinement pin bent and the closure leaked excessively. Suit C was not self-donnable; however, the leakage was considerably less than for the other two suits. Suit A was the quickest suit to don, but the zipper caught several times in the constant wear garment. (It should also be noted that this particular test subject has the unique ability to reach any part of his back.)
Donning and doffing gloves	Subject suited, gloves placed randomly under left knee (task was timed)	The time required to don the different types of gloves was not significantly different. Suit B gloves were the quickest to don, partly because of the longer sleeves. Sleeves of suit C seemed to interfere with quick donning of gloves because the sleeves seemed short.
Extravehicular (EV) visor operation at 3.7 psig	Subject at 3.7 psig, standing	EV visors for suits A and B were not acceptable because they were not functional. The EV visor for suit B would not lock onto the helmet and the EV visor for suit A could not be donned or operated properly.
Extravehicular (EV) visor donning and doffing at 3.7 psig	Subject at 3.7 psig, standing (task was timed)	
Opening and closing of gusset (if appropriate)	During donning	Operationally as well as functionally, the entries into all three space suits were inadequate. The neck ring donning in both suits B and C was adequate. Since suit A had a different means of entry, the neck ring donning of this suit was not investigated.
Bringing neck ring over head (if appropriate)	During donning (timed from start of maneuver to point when ring is completely over the head)	

TABLE III. - SUIT ADJUSTMENTS INCLUDING TASKS, CONDITIONS, AND ANALYSES - Concluded

Tasks	Conditions	Analyses
Adjust tiedown (if present)	Subject suited and standing, vented, and at 3.7 psig (timed from neutral position to extreme adjustment)	Suit C presented the best functional tiedown; however, this suit did not include a lock. Suit B's lock was difficult to release. The lock on suit A functioned adequately. The three types of tiedowns have no means to accommodate the excess webbing.
Connecting and disconnecting gas connectors	Subject lying in couch, lying on left-hand side, with and without gloves, both by looking and by feel (blind) (task was timed)	The times for connecting the gas connectors were not significantly different for the test conditions considered. This result is interesting because both suits B and C used multiple gas connectors, and suit A presented the subject with two separate connections to be made.
Connecting and disconnecting outside water connector	Subject standing, at 3.7 psig	Suit A did not supply a water connector. The water connectors on suits B and C were rather difficult to remove from the suit, and water connectors on both of these suits leaked air from inlet to outlet.
Operating diverter valve	Subject standing, suit vented and pressurized to 3.7 psig	Suit A did not furnish a diverter valve. The diverter valves of suits B and C were operational. A point worth noting is that only suit B had a diverter valve which was visible to the subject.
Reading the lock and unlock indicators on gloves	Subject standing, suit pressurized to 3.7 psig	The "lock" and "open" indicators of suit A were not always visible to the subject. On the other suits, these indicators were visible to the subject.
Connecting and disconnecting communciation cables at 3.7 psig and vented conditions	Subject standing, suit vented and pressurized to 3.7 psig	Because of its poor mounting location, the communications connector on suit C could not be connected or disconnected by the pressurized subject. Communication connectors of suits A and B were connected and disconnected with a minimum of difficulty.
Reading of pressure gage	Subject standing, suit pressurized to 3.7 psig	The pressure gages on all the suits were readable. However, the gage on suit B was read at an oblique angle, thus reducing the accuracy of the reading.

TABLE IV. - TASK PERFORMANCE TIMES

(a) Performance time for suit adjustments

Task	Mean time required for suit B	Mean time required for suit A	Mean time required for suit C
Suit donning (3 trials)	5.11 min	4.25 min	*7.84 min
Gloves donning (15 trials)	21.58 sec	24.7 sec	28.69 sec
Extravehicular visor donning (10 trials)	Subject gave up	Subject gave up	20.96 sec
Bringing neck ring over the head (10 trials)	2.30 sec	Not applicable	4.51 sec
Adjusting tiedown (10 trials)	Down: 10.54 sec Up (released): 11.16 sec	Down: 11.35 sec Up: 6.02 sec	Down: 5.20 sec Up: 2.72 sec
Connecting gas connector (mean for 40 trials)	5.6 sec	9.3 sec	5.8 sec
Connecting and disconnecting water connector (10 trials)	Connect: 4.26 sec Disconnect: 7.87 sec	Not applicable	Connect: 12.12 sec Disconnect: 4.79 sec

*Test subject wearing suit C did not complete the task without help.

(b) Time for connecting gas connector

Without gloves					
Looking			Not looking		
Suit B	Suit C	Suit A	Suit B	Suit C	Suit A
5.5 sec	3.8 sec	6.5 sec	8.1 sec	7.8 sec	10.5 sec
Wearing gloves					
Looking			Not looking		
4.6 sec	3.5 sec	6.5 sec	4.5 sec	8.2 sec	13.8 sec

9. Because of the poor location of the electrical connector of suit C, the communications connectors of suits A and B operated in a more adequate manner.

10. Because of the poor location of the pressure gage on suit B, the gages on suits A and C were more functional and could be read with more efficiency.

Based on test results, the following recommendations are made.

1. Extensive development should be initiated to produce a leakproof suit entry which is reliable and functionally easy to operate.

2. The glove connectors should be placed as close to the palm as possible, thereby reducing donning times and palm ballooning.

3. The extravehicular visor assembly of suit C should receive further study.

4. The tiedown of suit C with a simple lock should be used, since it is lighter and smaller, and quicker and easier to operate.

5. Any one of the three gas connectors could be used so far as operational connect and disconnect time is concerned.

6. The water connector on either suit B or C could be used because their times for connecting and disconnecting were the same.

7. The diverter valve should be made by the company that makes the gas connector.

8. In order for the subject to be able to read the words "lock" and "unlock" on the wrist disconnects for suit A, the words "lock" and "unlock" should be engraved through a greater arc thus stretching the word out, or engraved to appear several times around the wrist disconnect. Perhaps a more significant path of developmental inquiry is that which would lead to a wrist disconnect which would not require visual aid or more than one operation.

9. The communications connector should be located on the torso, so as to be well within reach of the pressurized subject.

Operational Mobility in the CM and LEM

Lunar excursion module studies. - In the interior access and mobility evaluation, the test subject wore the LCG and the PGA, and the suit was pressurized to 3.7 psig. For the ingress/egress studies, the pressurized subject wore the LCG, the PGA, the thermal meteoroid garment (TMG), and the latest configuration of the portable life support system (PLSS). The subject was timed for his ingress/egress through the front hatch. During this ingress/egress study, the front hatch was closed, thus requiring the subject to open the hatch. Following the ingress/egress evaluation for the front hatch, the test subject attempted to exit through the top hatch. For the LEM interior access and mobility study, the pressurized subject attempted to reach all areas in the LEM, including the area surrounding the ascent-engine cover.

Inside the LEM, suit A provided the subject a degree of mobility which was clearly superior to that afforded by the other two suits. In the pressurized suit A, the subject was able to reach all areas inside the LEM: he could sit on top of the ascent engine and reach back over each shoulder to the junction of the overhead and side well; and he could reach every part of the ascent engine and docking tunnel area. By moving either forward or backward, the test subject was able to mount the ascent-engine cover, and with considerable ease. In fact, the subject was able to put one foot on the deck next to the ascent engine while the other foot remained on the main floor. In both of the other suits, he was unable to mount to the engine cover and sit on it. On the contrary, he was forced to "thrash about" quite strenuously, placing his upper body over the ascent engine and reaching about in a rather marginal manner.

While pressurized and with the TMG and PLSS, all three suits allowed the subject to enter and exit through the front hatch in approximately 1 minute. Suit A, with the TMG top of suit C and the TMG pants of suit B, provided the test subject with enough mobility to almost succeed in exiting through the top hatch. He was prevented from doing so by the PLSS' rubbing too tightly against the tunnel edge. In the other two suits, the test subject was not able to ascend the engine-cover area.

Command module studies. - In this series of studies, the test subject wore the CWG and PGA, and the space suit was pressurized. The evaluation concerned the subject's capability to carry out mission tasks in the lower equipment bay area, including access to the lithium hydroxide (LiOH) canister area. In these CM studies, test results were also in favor of suit A. In all three suits, the subject was able to work in the lower equipment bay and in the LiOH canister panel area. However, suit A provided the greatest degree of mobility, allowing significantly greater ease and range of motion.

In the CM studies, another factor under consideration and evaluation was the elbow interface with the sidearm controller armrest and the degree of interference between the elbows of two pressurized subjects in the left and center couches. Suit A was clearly superior in this area also, because the subject could place his elbow in position and operate the attitude controller with a minimum of interference between his elbow and the elbow of the man in the next couch. In both other suits, this capability was highly questionable or totally unacceptable. In suit B, an extreme effort was required to position the right arm for controller operation, and the subject's elbow was 8 inches beyond the center line of the armrest. In suit C, the subject could not achieve the appropriate position: the elbow was more than 8 inches beyond the center line of the armrest; and the arm positioning brought about inadvertent pitch-down and yaw-left commands to the attitude controller in the no-load position.

Physiologic Tests

Metabolic cost. - The metabolic cost of operating in the different suits was determined by walking the subject on a treadmill at 0.8 mile per hour and 1.2 miles per hour when unpressurized, and at 1.5 miles per hour when pressurized to 3.7 psig. During the first test, these walking rates were established as the rates required to produce work levels of 800 and 1600 Btu per hour. The other two suits were exposed to the same walking rates, and the metabolic levels were monitored and compared. By means of the Scholander apparatus, metabolic rates were obtained by collecting expired gases and analyzing for O_2 and CO_2.

Carbon dioxide washout. - The CO_2 concentration in the oronasal area was determined at rest and during activity which approximated 800 and 1600 Btu per hour. The subject, with nose clip attached, breathed through a mouthpiece which had a tap for monitoring the CO_2 concentration. The level of CO_2 at the end of inhalation was taken as representative of the CO_2 concentration in the oronasal area. Suits B and C were also checked to determine the CO_2 washout effect by directing all the flow to the head (suit A did not have this capability). All exposures were continued until steady-state conditions were reached (a period of 4 to 6 minutes).

Ventilation adequacy. - The subject walked on a treadmill at 0.8 mile per hour for a 2-hour period. Nude and dressed weights of the subject were obtained for the pretest and post-test periods. Skin temperatures were obtained in five areas, and the temperature and dew point of the ventilating gas stream were monitored at the inlet and outlet to the suit. The suit pressure was maintained at 1.2 psig. Metabolic rates were determined every hour.

Analyses. - For the metabolic cost of walking when unpressurized, there was no significant difference between the suits (see table V). There were, however, significant differences in walking when pressurized to 3.7 psig. Under this condition, suit C was definitely superior.

Reference to table V demonstrates that suit A had the best CO_2 washout characteristics in the normal flow situation. Suit C CO_2 washout characteristics were competitive when all of the flow was directed to the head. This flow condition, however, would only prevail when the liquid cooled garment was being utilized.

Table VI summarizes all the ventilation data obtained. Suit C rated highest in ventilation efficiency and maintenance of low skin temperatures. The ventilation efficiency was computed as the change in weight between pretest and post-test nude weights. Suit C was exceptional in providing low skin temperatures in general, and in particular for the arms and back. Suit A had a ventilation efficiency close to that of suit C and a lower sweat rate. The low sweat rate of suit A was due in part to a high sensible heat loss to the gas stream and possibly to a greater heat transfer across the suit, since this was the only suit of those submitted that did not have a covering over the restraint layer. Although suit A generally produced considerably higher skin temperatures than suit C, it did produce low calf temperatures indicating good ventilation for the legs. Suit B compared unfavorably with the other two suits in both ventilation efficiency and sweat rates, and gave resultant skin temperatures similar to suit A.

Results

In the operational functions test, suit A rated first in six of the seven subtests. Results of each subtest may be summarized as follows.

Reach in the command module. - The operational reach of suit A was clearly superior to that of the other two suits. This was true for both the right and left hands, under both the vented and pressurized conditions.

Visual field in the command module. - The visual field for suit A was superior to both other suits; however, the visual field of suit C was similar to the vision obtained in suit A. Major weaknesses of the suit B helmet are the restrictions brought about by the communications cap and the basic configuration of the visor area. In terms of the visual field, there is a large difference between suit A and suit B.

TABLE V. - SUMMARY OF METABOLIC DATA

Type of space suit	Treadmill speed, mph	Metabolic rates, Btu/hr	Pressure, psig	Pressure of CO_2, mm Hg	
				N (a)	FTH (b)
Suit C	At rest	400	1.2	4.56	- -
	0.6	674	1.2	- -	- -
	0.8	919	1.2	9.12	6.46
	2.5	1575	1.2	12.92	6.84
	1.5	1268	3.7	13.30	9.50
Suit B	At rest	400	1.2	6.84	- -
	0.6	745	1.2	- -	- -
	0.8	930	1.2	7.60	6.46
	2.5	1688	1.2	10.26	9.88
	1.5	1985	3.7	12.16	11.40
Suit A	At rest	400	1.2	3.42	- -
	0.6	786	1.2	4.56	- -
	0.8	833	1.2	6.08	- -
	2.5	1459	1.2	8.74	- -
	1.5	1665	3.7	9.50	- -

[a]N = Normal flow distribution.

[b]FTH = All flow directed to helmet.

TABLE VI. - VENTILATION DATA

Parameter	Suits		
	Suit A	Suit C	Suit B
Weight loss, g	525	685	850
Metabolic rate, Btu/hr	792	734	790
Computed insensible weight loss, g	134	119	135
Computed sweat rate, g/hr	195	282	357
Sensible heat loss, Btu	80	48	60
Ventilating efficiency, from weights, percent	88	95	70
Mean skin temperature, °C	35.2	34.4	35.2
Back	34.9	33.8	34.6
Chest	35.3	35.3	35.3
Calf	34.7	34.9	39.5
Arm	35.6	33.7	35.7
Forehead	35.4	34.5	34.3

Reach in the lunar excursion module. - For operational reach in the LEM, suit A was significantly superior to the other two suits. Reach of suit B exceeded that of suit C, and suit C showed particular restrictions in shoulder adduction (that is, in moving the arm across the body to reach the opposite side). Restrictions in shoulder adduction also applied to suit B but not to the significant extent as for suit C. In shoulder adduction, suit A was far superior to the other suits.

Visual field in the lunar excursion module. - Operational vision requirements of the LEM are met fairly well by all three suits, but suits A and C have superior vision capabilities when compared with suit B. This is especially true for lateral and upward vision. Upward vision is the more critical because sighting for docking is made through the overhead docking window. In suit B, the communications cap slips down the forehead and blocks vision.

Suit adjustments. - For this subtest, 13 different adjustment tasks were performed and rated along the nine-point scale. Final tabulation assigned first place to suit A, second place to suit B, and third place to suit C. Suit A was the quickest suit to don, but the zipper caught several times in the constant wear garment. Suit B was donned more rapidly than suit C; but it should be noted that the alinement pin in suit B bent, and the closure leaked excessively.

Mobility in the CM and LEM. - Suit A offered superior operational mobility in this subtest, showing a significant magnitude of difference over suits B and C. Not only was the test subject able to carry out a wider range of mobility tasks with suit A, but he was able to do so with greater efficiency and with much less effort. Mobility concepts manifested in suit A appear to have significant developmental impact, and they offer the best potential for meeting mission requirements.

Physiologic subtest. - Final results of the physiologic subtest indicate that suit A and suit C are similar in overall performance ratings, and that both are superior to suit B. Suit A was rated slightly above suit C. There may be some question as to the validity of conducting this subtest with just one subject, but the main objective of this subtest was to obtain a comparison of the three different space suits and to establish whether the results were acceptable. With these objectives in mind, it is felt that the test program is valid.

ENGINEERING TEST

The engineering test, consisting of nine subtests, accounted for 33 percent of the total score for each space suit. The subtests concerned pressure drop, leakage, helmet design, component functions, dimensions, weight, inspection, proof pressure, and centrifuge tests. Table VII shows the relative weights of the subtests, their objectives, and the equipment necessary for carrying out the subtests.

Pressure Drop Tests

The flow rate was measured at the console, using a rotameter calibrated in standard cubic feet per minute (scfm) at 18.4 psia (pounds per square inch absolute). The suit inlet temperature and pressure were measured slightly upstream of the suit inlet connector. The total-system pressure drop was obtained by tapping points immediately adjacent to the inlet and outlet connectors. The vent-system pressure drop was obtained by tapping points in the vent ducting immediately adjacent to the connector body, one tap being in the supply duct and the other in the return duct.

Test procedure. - With the space suit occupied, the pressure drops of the total system and vent system were measured for the standing position, and the total-system pressure drop was measured for the couch position. The couch-position measurements were taken with the restraint system in place, and with the straps taken up but not pulled tight. It was felt that this condition was more realistic in view of the fact that most of the intravehicular time in the couch will be spent with little or no restraint.

The couch and the standing position pressure drops were measured for identical inlet conditions. Since the connector configuration does not change with body position, any difference in pressure drop for the two positions is due to the change in vent-system configuration.

The measured data were converted to extrapolated pressure drops at the design conditions. To extrapolate from sea level conditions to altitude conditions, assume the following holds over the pressure range:

$$\rho \, \Delta p = k(m)^n$$

TABLE VII. - SUBTESTS OF THE ENGINEERING TEST

Subtests	Objectives	Necessary equipment
Subtest 1 (weight 4); pressure drop	To determine the pressure drop characteristics of the PGA's for the three space suits.	Suit checkout console, water manometer, and differential pressure tap fittings
Subtest 2 (weight 4); suit leakage	To determine the amount of oxygen leakage for each of the three space suits; the leakage was measured in standard cc/min, at 0.18 psig and 3.7 psig.	Flowmeters and water manometer
Subtest 3 (weight 7); helmet design	To evaluate, in terms of engineering design, the components of the helmets for the three space suits.	None
Subtest 4 (weight 13); component functions	To determine the functional-design adequacy and operational capability of suit components relative to mission requirements.	Equipment appropriate for the subjective analyses
Subtest 5 (weight 5); dimensions	To determine various critical dimensions, in both the standing and sitting positions, with suits pressurized to 3.7 psig; also, to determine the minimum stowage volumes for the helmet and limb-torso suit.	Anthropometer, steel measuring tape, and outside calipers
Subtest 6 (weight 3); weight	To determine the weight of selected components for the three space suits, and to rate each component in terms of established specification requirements.	Gram scale
Subtest 7 (weight 5); inspection	To evaluate the quality of workmanship, materials, and general overall appearance of the suits.	None
Subtest 8 (weight 2); proof pressure	To determine whether the suits could withstand proof pressure, and the extent of suit degradation due to this pressure.	Suit-pressure test console
Subtest 9 (weight 4); centrifuge tests	To determine if pressure points were produced by the size, weight, and location of various suit components; and to determine if the combined helmet-couch configuration results in an acceptable aortic-retinal angle under sustained acceleration.	Centrifuge, simulated Apollo couch, bioinstrumentation, and related items

where k and n are constants, then:

$$\Delta p_a = \Delta p_s \left(\frac{\dot{V}_a}{\dot{V}_s}\right)^n \left(\frac{p_a R_s T_s}{p_s R_a T_a}\right)^{n-1}$$

where:

m = mass flow rate, lb/min

p = pressure, lb/ft^2, absolute

Δp = pressure drop, inches of H_2O

R = gas constant = 48.3 ft-lb/lb-°R for O_2

T = temperature, °R

$\dot{V}$ = volume flow, cu ft/min

ρ = gas density, lb/ft^3

a = altitude conditions, design point

s = sea level conditions

Sample calculations for suit B are as follows:

<u>Sea level measurements:</u>

p_s = 18.4 psia

$\dot{V}_s$ = 12 scfm = 9.6 actual cubic feet per minute (acfm)

T_s = 66° F = 526° R

$R_s = R_a$

Δp = 13.0 inches of water (manned, couch position)

Design point conditions:

$$p_a = 3.5 \text{ psia}$$

$$T_a = 50^\circ \text{ F} = 510^\circ \text{ R}$$

$$\dot{V}_a = 12.0 \text{ acfm}$$

Assume $n = 1.8$ (laminar/turbulent flow), then:

$$\Delta p_a = 13.0 \left(\frac{12.0}{9.6}\right)^{1.8} \left[\frac{(3.5)(48.3)(526)}{(18.4)(48.3)(510)}\right]^{0.8}$$

$$= (13.0)(1.25)^{1.8} \ (0.196)^{0.8}$$

$$\Delta p_a = 5.3 \text{ inches of } H_2O$$

Results of the pressure drop tests are shown in table VIII.

Analysis. - Test results indicate that suit B placed first in the ratings. The rating of space suits in this test was complicated by the fact that suit C was submitted with both vehicle and PLSS multiple gas connectors (MGC), suit B was submitted with only a PLSS multiple gas connector, and suit A was submitted with Gemini-type gas connectors.

Suit C was rated as unacceptable because the pressure drop in the vent system alone exceeded the specification value for both vent system and gas connector.

Suit B was acceptable, even though it slightly exceeded the allowable pressure drop, when using the PLSS connector. By extrapolating the reduction in system pressure drop which would result from using a vehicle gas connector instead of the PLSS connector, it was estimated that suit B would meet the specification limit.

For suit A, the total-system pressure drop was within the specification limit. However, the vent-system pressure drop was too high to allow the use

TABLE VIII. - PRESSURE DROP TEST RESULTS

Suit and position	Total system Δp, in. of H_2O (a)	Extrapolated to design point (b)	Vent system Δp, in. of H_2O (a)	Extrapolated to design point (b)	Remarks
Suit C, standing	39.2	16.0	13.7	5.6	Multiple gas connector, PLSS half
Suit C, couch	44.0	18.0	[c]18.5	7.5	
Suit B, standing	11.9	4.9	2.8	1.1	Multiple gas connector, PLSS half
Suit B, couch	13.0	5.3	[c]3.9	1.6	
Suit A, standing	9.0	3.7	8.0	3.3	Gemini-type gas connectors
Suit A, couch	9.0	3.7	8.0	3.3	

[a]Sea level tests at "normal flow" and normal inlet conditions: 12.0 standard cu ft/min; 3.7 psig; 70 F; 100 percent O_2.

[b]Design point conditions at inlet. (Specified Δp limit = 4.7 in. of H_2O): 12 acfm; 3.5 psia; 50° F; 100 percent O_2. (See sample calculations for extrapolation.)

[c]Computed value.

of a multiple gas connector. The Gemini-type gas connectors have a very low pressure drop, but they do not meet the requirements that determine the design of a multiple gas connector (MGC). Therefore, suit A rated barely acceptable on the test.

Suit Leakage

Test procedure. - The space suits were unoccupied, and a set of standard procedures was followed in preparing the suits for testing. Each suit was subjected to two leakage tests. The pressure garment assembly was pressurized with O_2 to 0.18 psig, and leakage was recorded after the rotameter was stabilized for 10 minutes. The pressure garment assembly was then pressurized to 3.7 psig, and leakage was recorded after the rotameter was stabilized for 10 minutes.

The leakage was measured in standard cubic centimeters per minute (scc/min) at 0.18 psig and 3.7 psig. Standard conditions were defined as 29.92 inches of Hg and a temperature of 70° F. To insure that seals had not been abnormally seated at higher than leakage test pressures, the separable portions of the suit (that is, helmet and gloves) were removed and remained unpressurized for at least 15 minutes before the leakage tests were conducted. During the leakage tests, pressure was not increased in excess of the values specified.

Analysis. - When final scores were computed, suit C was rated as superior to the other two suits. Final test results indicated that both suit A and suit B had leakages in excess of 3000 scc/min at 3.7 psig. Suit C had a leakage of less than 700 scc/min at 3.7 psig.

During the suit A test, a 1-hour hold was granted, according to prearranged guidelines, to make repairs to the right knee bellows and to the helmet neck ring. During further testing, leakage was found at the upper and lower part of the zipper. Suit A was originally given a zero for the suit leakage tests because it did not meet the delivery date. However, the data cited here were gathered during a rescheduled test. At 0.18 psig, leakage for suit A was approximately 700 scc/min.

Testing at 3.7 psig indicated that leakage for suit B was in excess of the instrumentation capability of 3500 scc/min. A meeting was held with the contractor representatives who said the leakage could not be lowered in the 1-hour period provided in the test guidelines. Suit leakage at 0.18 psig was approximately 3000 scc/min.

Leakage for suit C was approximately 500 scc/min for both the 0.18 psig and 3.7 psig tests. This leakage was not as low as will be required for all future space suits.

Helmet Design

Test procedure. - This subtest consisted of a subjective evaluation by a seven-man evaluation team which rated each helmet component according to prearranged analysis areas. Analysis areas for rating the helmet design and communications carrier design were reliability, susceptibility to damage, weight, volume, simplicity, and materials. Analysis areas for rating visor optics were distortion, reflection, and clarity. Analysis areas for the feed port design were reliability, susceptibility to damage, weight, simplicity, materials, volume, and suit reliability.

Analysis. - Final ratings indicate that suits A and C had helmet components which were built in a more reliable and simple manner than the helmet components of suit B. The feed port of suit B is not simple from the standpoint of the number of parts (21), but it is simple from the operational standpoint. The feed port of suit B required two helmet penetrations, and this is not desirable in an apparatus which is used only as an emergency device. In addition, this feed port is not snagproof.

The feed port of suit A does not have a redundant seal or lock, and this is not desirable because it is used only in an emergency situation. The feed port of suit C is similar to that of suit A, and it is not acceptable because of its low reliability and lack of simplicity. In addition, the feed ports of both suit A and suit C are susceptible to being opened by the microphones when the subject moves his head inside the helmet.

The visor optics of suit B approximate acceptable limits, while the visor optics of the other suits are not within acceptable limits.

The communications carrier of suit B is unacceptable for impact, but other areas such as reliability and simplicity are generally acceptable. For suit B, the communications carrier forehead bar falls over the eyes and restricts vision, and the microphones have no means for placement. Also, the carrier provides no means of perspiration absorption, and it causes pressure points on the sides of the head.

The communications carrier of suit A is not acceptable because of lack of comfort, reliability, and appropriate materials. The communications carrier of suit C is basically weak due to its exposed insulated wires; however, this did not cause any problems during testing. Nevertheless, the potential for creating serious problems is clearly present. The forehead perspiration band of suit C should be fixed to eliminate its slipping downward and restricting upward vision. All three carriers have unacceptable means of head attachment.

The following statement clarifying the issue concerning impact is quoted from NASA and Holloman Air Force Base impact-drop personnel: "The helmet of" (suit B) "the sliding cable suit appears to be unacceptable for the level of human impacts expected during the Apollo mission. A dangerous pressure point on the lateral side of the astronaut's head can occur during impact because of the large size of the earphones. This would not be a problem with the earphones during a pure traverse EBI (eyeballs in) acceleration; however, the greater the lateral component of acceleration (eyeballs left or eyeballs right) during impact, the more dangerous the problem becomes. The brace across the forehead also presents a potentially dangerous object. Here again the lateral acceleration component of impact is the more dangerous since rolling and turning of the head inside the helmet can tear loose or break the brace and/or ram it into the astronaut's face. No particular objections could be found with the helmet of" (suit C) "the link net suit. The smaller size of the earphones (they could be smaller) plus the insert should prevent a problem area during lateral components of acceleration."

The three helmets are of the same basic size and configuration; however, the helmet of suit B is not a one-piece shell, and its visor is not uniform in symmetry. This helmet's fiber-glass shell is pinned and bonded to a polycarbonate visor, and this construction restricts the wearer's binocular vision in those areas provided for in the other helmets. This type of construction also results in a reduced total visual field as compared with the helmets of suits A and C. Further, the helmet of suit B is fabricated of many more parts, and contains a multiplicity of penetrations, whereas the other helmets have only two penetrations. The helmet of suit C is much more reliable and is simpler than the helmet of suit B, and it can be fabricated from superior materials as compared with the suit B helmet.

Component Functions

Test procedure. - This subtest involved 10 subsections which evaluated gas connectors, wrist disconnects, suit entry, neck ring, pressure gage, relief valve, water connector, gloves of the pressure garment assembly, extravehicular visor, and electrical harness. For each of these subsections, appendix B gives information on specific test objectives, procedures, and results.

Analysis. - Final results of the component functions evaluation are too close to indicate that any one space suit exceeded the others in all areas. In general, results indicate that all three space suits were below the acceptable limits in most phases of component functions. Of the 10 subsections, suit A and suit C did present acceptable neck rings; however, these can easily be improved to exceed the minimum requirements. Suit C also presented an acceptable extravehicular visor assembly, but this assembly also requires further development. Suit B did not meet or exceed the minimum acceptance level in any phase of the component functions test. Final results, which are given in detail in appendix B, may be summarized as follows.

Gas connectors: Of the three gas connector arrangements evaluated, the connector of suit B best approached the general requirements. It is recommended that the gas connector of this suit, with appropriate modifications, be used in future suits.

Wrist disconnects: From a functional and operational standpoint, the evaluation indicated that the wrist disconnects for all three suits were not adequate for the mission. The steel paws in the connector of suit C were superior to the Delrin paws of suits A and B. It is suggested that the design requirements and rationale be studied and modified to enable the connector to be simplified to the point that it would be acceptable for the mission. It is recommended that paws be eliminated from the design, and that they be replaced by a simpler mechanism.

Suit entry: The three suit entries were not acceptable for the mission. It is recommended that a gusset closure be used on the Apollo suit because of its greater simplicity and reliability as compared with a zipper.

Neck ring: The neck ring designs for all three suits were conceptually similar. The neck ring of suit C was considered superior to neck rings of the other two suits.

Pressure gage: Except for suit checkout, the pressure gages of suit A and suit B would suffice for the Apollo mission. Location of the gage on the lower left arm is satisfactory on suit A, but the gage should be moved inboard approximately 1 inch on suit B. From the standpoint of reliability and readability, the mounting technique used on suit C is not acceptable. Also, the faceplate scale on the gage of suit C is not arranged correctly for the Apollo mission.

Relief valve: In terms of operating characteristics, the valve of suit C is slightly superior to that of suit B and highly superior to that of suit A. However, suit reliability was not degraded appreciably by any of the valves.

Water connectors: Final evaluation indicated that suit B ranked in first place, but it was rated slightly less than completely acceptable because of the lack of gripping provisions on the male halves. For this test, suit A was given a zero because the company submitted no water connector for evaluation. The water connector of suit C was rated as only marginally acceptable. The water connector of suit B, with certain minor modifications, is recommended for use on future suits.

Gloves of pressure garment assembly: The PGA gloves of suit C were rated in first place according to the standard scale used throughout this evaluation program. However, there were no distinct advantages in any of the gloves, and none of the units was considered as fully meeting mission requirements.

Extravehicular visor assembly: Final rating gave first place position to suit C, second place to suit A, and third position to suit B. It was evident from the broad differences that the visor concept of suits A and C should be followed.

Electrical harness: In this area, suit B rated first, but there was little difference between suits B and C. As for material, the rating for all three harnesses was given a zero. The harness of suit A used materials not acceptable for production. Harnesses of suits B and C used silicon rubber. Suits B and C used connectors specified by NASA, while suit A did not.

Suit Dimensions and Stowage Volumes

Test procedure. - The test subject donned the constant wear garment and the pressure garment assembly, and suit dimensions were measured. Measurements were taken at a vented pressure of 0.18 psig and when the suit was pressurized to 3.7 psig. Under both of these conditions, measurements were taken with the subject standing in a comfortable relaxed position, and with the subject sitting in a comfortable position on a flat surface in such a way that the boots did not touch the floor. The amount of stowage volume was determined for the helmet, limb-torso suit with gloves attached, constant wear garment, and thermal meteoroid garment.

The relaxed condition at 3.7 psig was used in the final evaluation. The dimensions across the shoulders, elbows, and knees were the only ones used in the evaluation, because these areas were considered to be the most critical. In arriving at a rating for suit dimensions, the shoulder and knee dimensions were each assigned a weight factor of 2, and the knees a weight factor of 1.

Although several stowage volumes were determined, the evaluation included only the helmet and the limb-torso suit. The manner in which the limb-torso suits were folded for determining the stowage volume could probably be improved by ascertaining the optimum technique for folding. In arriving at a rating for stowage volumes, the limb-torso suit was assigned a weight factor of 2.5, and the helmet a weight factor of 1.

In arriving at a rating which included suit dimensions and stowage volumes, suit dimensions carried a weight factor of 3 and stowage volumes carried a weight factor of 1.

Dimensions. - When space suits were rated according to critical dimensions, suit A was in first place, suit C was second, and suit B was third. Specific dimensions for the three suits (pressurized) were:

Space suit	Shoulder	Elbow	Knees
Suit B	23.6 in.	32.6 in.	17.0 in.
Suit A	22.7 in.	28.1 in.	16.5 in.
Suit C	22.4 in.	33.8 in.	14.5 in.
Specifications	24.0 in.	24.0 in.	16.0 in.

All suits had the exceptional quality of more than complying with the shoulder dimension specification requirement of 24 inches. However, the opposite was true for the elbow dimensions, in which case all suits exceeded the specification requirement of 24 inches. Suit C was the only space suit to meet the knee dimensions specification of 16 inches, and it was approximately 1.5 inches less than the specification.

Suit dimension across the shoulders of suit C, in the pressurized-relaxed condition, was less than for the other two suits. The suit dimension across the elbows of suit A, in the pressurized-relaxed condition, was less than for the other two suits.

Based on these test results, it appears that considerable development effort is required to meet the requirement for a 24-inch pressurized elbow width. So far as elbow dimensions and mission requirements are concerned, an extensive study is recommended for the relationship between the current state-of-the-art and the anticipated state-of-the-art.

Stowage volumes. - When space suits were rated according to stowage volumes, suit A rated in first place, suit C second, and suit B third. Specific stowage volumes for the three suits were:

Space suit	Helmet	Limb-torso
Suit B	2200 cu in.	3900 cu in.
Suit A	1713 cu in.	3690 cu in.
Suit C	2050 cu in.	3240 cu in.
Specifications	2275 cu in.	5760 cu in.

All suits met the specification requirements for the helmet and for the limb-torso suit. The helmet stowage volume for suit A was less than that for suits C and B by 337 and 487 cubic inches respectively. The limb-torso suit stowage volume for suit C was less than that for suits A and B by 450 and 660 cubic inches respectively.

Dimensions and stowage volumes. - When weight factors were considered, and both the dimensions and the stowage volumes were included, the overall rating ranked suit A in first place, suit C in second, and suit B in third. There was little difference between the overall ratings of suits A and C.

Weight

Test procedure. - A standard procedure was established for weighing all components. Each component was dry and was carefully checked to make sure that all subcomponents were attached. All components were weighed on the same balance, and the scale was returned to zero after each component was weighed. Prior to weighing, the gram scale was balanced at zero (to the nearest gram) and was checked after each component weight. Each component was weighed to the nearest gram.

The weights of all components were recorded, as indicated in table IX, but the overall rating for the suits included only the helmets, gloves, limb-torso suits, and extravehicular visors. For these areas, the helmets were assigned a weight factor of 2, the gloves a weight factor of 1, the limb-torso suits a weight factor of 4, and the extravehicular visors a weight factor of 1. The other components were not required for this evaluation.

For a particular suit, a component or other piece of hardware may not be required because of difference in design. It was decided that absences of weights such as these would not be reflected in this analysis of component weight, but would be reflected in the evaluations of other subtests. The absence of such weight factors was intentionally eliminated from the component

TABLE IX. - COMPONENT WEIGHTS

[In grams]

Type of suit	Helmet with communications	Gloves, pair	Limb-torso suit	PGA (a)	EV visor assembly	Water garment	Constant wear garment
Suit B	1865	494.5	10 870	13 229.5 (29.2 lb)	1325	1483	268
Suit A	1216	638	10 590	12 444 (27.4 lb)	1007	0	0
Suit C	1203	649.5	8 730.5	10 583 (23.3 lb)	1169.5	[b]1029.5	312

[a]Weight of PGA represents sum of weights for helmet, gloves, and limb-torso suit.

[b]Weight included no connectors.

weight evaluation, because the components were selected with this problem in mind and because weighting factors were used for the components.

Analysis. - When the space suits were rated according to component weights, suit C was in first place, suit B was second, and suit A was third.* There was little difference between suits A and B.

The helmets of suits A and C were approximately 1.5 pounds less than suit B, and almost 3 pounds below specification requirements. Also, the weight of gloves for suit B was approximately 25 percent below the glove weights for suits A and C. In addition, the weight of the limb-torso suit for suit C was approximately 4.5 pounds below that of the other two suits, and about 0.75 pound below specification requirements. The extravehicular visors were 0.50 pound higher than expected.

The weights, as measured in this test, indicate that the complete pressure garment assembly can be delivered well within the specification weight requirements.

Inspection

Test procedure. - On receipt of suits B and C, the components of each suit assembly were inspected. Suit A was inspected after the suit had been presented to NASA and after it had been tested at the Grumman Aircraft Engineering Corporation. These suit inspections represent the pretest inspection.

Standard inspection procedures were applied to all three suits, and each suit was inspected as part of the suit evaluation program. To determine whether or not any conditions had changed between the pretest inspection and the final inspection, the difference between the mean ratings of the two inspections was computed.

The suits were divided into component areas (helmet shell, bump hat, boots, and gloves, for example), and each area was inspected according to standardized inspection criteria.

*The total weights, as presented in table IX, tend to show suit A as being second and suit B as third. However, it should be noted that the rating system used in this evaluation considered positive and negative aspects of meeting or failing to meet specification values, thus allowing extra value points for exceeding the specification value in a superior manner and detracting value points for failing to meet specification values. Since there were situations in this particular test where both such events occurred, the resulting weighted ratings brought about the final results reported here.

Analysis. - Mean values for each component area of the pretest inspection were computed, along with the differences between mean rating values for pretest inspection and final inspection. Based on inspection ratings, the final results ranked suit A in first place, followed by suit C in second, and suit B in third. According to the scale used in this evaluation program, there was little difference between suits A and C.

In general, suits A and C were neatly assembled and clean, while suit B was not. Suit A was weak on proper identification of certain components, and several of the components of suit C had sharp edges and corners.

Concerning suit B, the stitching was very poor, uneven, broken, not locked, and in some places not sewn. Several of the components for this suit had excess cement on them, were sharp, and had loose or improperly fixed screws. The gusset alinement pin for this suit was bent and pointed, and the length of the neck ring hinge arm was too short. A final point for consideration was that suit B was assigned post-test inspection ratings which resulted in greater mean differences than for the other two suits, thus showing a greater degradation in suit condition.

The quality of craftsmanship in suits A and C was clearly superior to that shown in suit B. It is recommended that future space suits be fabricated with a quality of craftsmanship equal to or better than that shown in suits A and C.

Proof Pressure

Test procedure. - The unoccupied space suits were inspected and assembled according to standardized procedures. Excluding the constant wear garment, and with an ambient temperature and pressure, the internal pressure of the pressure garment assembly was slowly increased from 0 to 8.0 psig $\pm$ 0.1. This pressure was held for 10 minutes.

Analysis was based on the evaluation team's inspection. The inspection criteria, used for establishing a base for ratings, were:

1. Were outer surfaces free from scratches and abrasions?

2. Was all stitching tight and unbroken?

3. Was material under and adjacent to stitching free from tearing and separation?

4. Were all cemented seams free from separation and was the bond adequate?

5. Was the restraint layer undamaged?

6. Were there broken or overstressed threads on mounting tapes?

7. Was neck ring undamaged?

8. Was neck ring seal undamaged?

9. Did neck ring locking mechanism operate properly?

10. Was neck ring hinge free in operation?

11. Was front holddown buckle, including locking latch, free from damage?

12. Were gas connector screws tight?

13. Was there smooth operation of gas disconnect unlock tabs?

14. Were electrical connector pins straight and was case undamaged?

15. Was electrical connector socket undamaged?

16. Was helmet shell free from scratches and cracks?

17. Was helmet neck ring free from chips, galling, and distortion?

Analysis. - Based on the standard rating scale, suit C ranked in first place, suit A in second, and suit B in third. All suits passed the proof pressure test with no structural failures. Suit B showed overstressed and broken threads which were rated as degradation; however, this condition did not contribute to or constitute structural failure. It was also noted that the holddown strap of suit B was being badly chafed by the strap buckle. The restraint cords of this suit were also rated as marginal because it was observed that some of these cords were becoming loose and untied. Inspection of suit A revealed degradation in the neck ring and helmet area. For suit C, there were no significant signs of degradation.

Centrifuge Tests

Test procedure. - The suited subject, complete with constant wear garment, bioinstrumentation, and electrical harness, was subjected to the following g-spectrum:

2g for 60 seconds - 1.5g/sec rise - 96° hip angle (familiarization run)

5g for 60 seconds - 1.5g/sec rise - 96° hip angle

10g for 25 seconds - 1.5g/sec rise - 96° hip angle

Pressure points were determined by the subject's comments during the sustained accelerations and by an examination of the subject's body following the centrifuge runs. These results were rated by members of the evaluation team. After each centrifuge run, the test subject was given a suit schematic on which to indicate the pressure points, along with his responses to a questionaire on comfort.

The aortic-retinal angle effects were investigated by placing peripheral lights in front of the test subject. The point at which vision would start to "tunnel" (decrease in peripheral vision) would indicate an inappropriate aortic-retinal angle.

The following parameters were recorded and displayed in real time: EKG No. 1, EKG No. 2, respiration, suit outlet temperature, acceleration, peripheral and center lights "ON," and the subject's response to lights. All voice communications were recorded.

Suit A was not included in the centrifuge tests because the suit did not meet the test schedule date.

Suit C. - The subject had no difficulty donning the suit, and no pressure points were noted prior to the runs. During the 2-g run, the subject experienced a pressure point on top of the head. However, prior to the 5-g run, it was noticed that the helmet ring was riding on the underside of the helmet support, causing the helmet to be forced against the top of the head. The pressure point was eliminated by turning the helmet rest 180°.

The only pressure point noted during the runs was a slight pressure point on the right thumb. While correcting the pressure point on top of the head, prior to the 5-g run, the suit was noticed to be slightly pressurized to approximately 0.5 psig. Whether or not this would substantially affect the runs could not be determined, and no corrective action could be taken due to available instrumentation.

Under sustained acceleration, the suit-helmet-couch configuration did not produce an aortic-retinal angle that resulted in loss of peripheral vision. At high g-loadings, the microphones tended to impinge on the face.

Suit B. - The test subject had trouble donning the suit, and this trouble stemmed from excessive material in the boot area and a tendency for the vent tubes to fold over in the boot. Prior to the runs, a pressure point was noted in the small of the back and on top of the shoulders.

During the 2-g run, the subject noted that there were moderate pressure points in the small of the back, on top of the head, across the shoulders, on the lower back at cable guides, and at the fingertips. The subject stated that the pressure points did not increase in magnitude between the 2-g and 10-g runs. In addition, the pressure point on top of the head did not exist during the 10-g run. The metal bar on the communication carrier had a tendency to slide down toward the eye level.

Suit pressure was not monitored due to available instrumentation, but suit support-engineering personnel judged the suit pressure to be at vent pressure. Flow was measured at the end of the 10-g run; but instrumentation would not indicate below 5 scfm, and the pressure was estimated at 3 scfm.

There was no tunneling of vision during the entire g-spectrum, thus indicating that the suit-helmet-couch configuration did not produce an unacceptable aortic-retinal angle.

Analysis. - Based on the standard rating scale, suit C ranked in first place and suit B in second place. The centrifuge tests resulted in the following conclusions.

1. No major pressure points were noted during sustained accelerations.

2. For the conditions studied, the eye-to-heart angle was satisfactory for both suits.

3. Pressure points at 2g did not increase in severity as the runs increased to 10g.

4. Throughout the runs, suit C was more comfortable than suit B.

5. For both suits, pressure points were produced on the calf of each leg.

6. Suit A received a zero for this test because it did not meet the test schedule date.

7. During the g-load runs, the test subject noted that he was able to nod his head (neck flexion) to some degree in the helmets of both suits.

It is recommended that further studies be carried out to ascertain the implications relative to the subject's ability to nod his head within the helmet during g-loading.

Results

In the engineering test, suit C rated first in six tests, suit A was first in two tests, and suit B was first in one test. Results of each subtest may be summarized as follows.

Pressure drop. - From the standpoint of pressure drop, suit B (with multiple gas connector) was superior to the other two suits, and suit B was the only one of the three that came close to meeting all requirements. However, if a gas connector arrangement with a much lower pressure drop than the multiple gas connector were acceptable, suit A might also meet the specification requirements.

Leakage. - This test indicated that both suit A and suit B had leakages that were in excess of 3000 scc/min at 3.7 psig. Suit C had a leakage of approximately 500 scc/min for both the 0.18 psig and 3.7 psig runs. Although the leakage of suit C was not as low as Crew Systems Division will require on all future suits, it was felt that this was acceptable. Suit C rated first and was far superior to the other suits.

Helmet design. - Final ratings indicated that suits A and C had helmet components which were built in a more reliable and simple manner than those of suit B. It was concluded that the helmet of suit C was significantly more advanced and provided superior visual field, quicker donning capability, less weight, and greater reliability than the helmets of the other two suits.

Component functions. - This test consisted of evaluations for 10 different component functions. Final ratings were too close to indicate that any one space suit exceeded the others in all areas; however, suit C was rated as first, followed by suit B and suit A. In general, the ratings indicated that all three space suits were below the acceptable limits in most phases of component functions.

Dimensions. - All three suits had measurements across the shoulders that were less than the specification requirement of 24 inches. The opposite was true for the elbow dimensions, where all the suits exceeded the specification requirement of 24 inches. Space suit C was the only suit which met specification requirements for the knee measurement. Concerning stowage volumes, all three suits met the specification requirements for the helmet and limb-torso suit. In some cases, these stowage volumes were considerably lower than requirements.

Weight. - In this subtest, suit C was rated in first place, suit B in second, and suit A in third. There was no significant difference between the ratings of suits A and B. Component weights, as measured in this test, indicate that the complete pressure garment assembly can be delivered well within the specification weight requirements.

Inspection. - In this evaluation, suit A rated first, suit C second, and suit B third. There was little difference between the ratings of suits A and C. In general, the quality of craftsmanship in suits A and C was clearly superior to that shown in suit B. It was recommended that future suits be fabricated with a quality of craftsmanship equal to or better than that shown in suits A and C.

Proof pressure. - All three suits successfully completed the proof pressure test, and there were only small differences among the suits.

Centrifuge tests. - Only two suits were evaluated in this test because suit A did not meet the test schedule date. Suit C rated first and suit B second. There were no major pressure points noted during sustained accelerations. Suit C was rated as being more comfortable throughout the entire run.

BASIC FUNCTIONS TEST

This test, consisting of five subtests, accounted for 17 percent of the total score for each space suit. Table X gives the relative weights of the subtests, their objectives, and the equipment necessary for carrying out the subtests.

General Mobility

The general mobility subtest consisted of two studies, an angular range of motion study and a strobe and movie sequences study.

TABLE X. - SUBTESTS OF BASIC FUNCTIONS TEST

Subtests	Objectives	Necessary equipment
Subtest 1 (weight 6); mobility, general, and ranges of motion	To obtain measures of the angular range of excursion for certain elementary movements; and to compare suits on selected mobility maneuvers under conditions including vented and pressurized state, with and without TMG, with and without LCG or CWG, as determined by goals.	Mobility notation table and flexometers, communications and pressurization monitoring equipment, strobe and movie filming techniques.
Subtest 2 (weight 3); eye-heart angle and X-ray study	To determine eye-heart angle and angular loss of joint mobility for the pressurized state.	X-ray facilities, mockup Apollo couch (left couch), appropriate pressurization and communications equipment.
Subtest 3 (weight 5); maximum visual field	To ascertain maximum visual-field capability for each test suit.	Optical perimeter, support device, and necessary communications and pressurization equipment.
Subtest 4 (weight 4); hand dexterity	To provide an objective measure of hand and finger dexterity in the suited condition.	Purdue pegboard test.
Subtest 5 (weight 4); functional reach	To obtain functional reach envelopes for the suited subject at both vent and 3.7 psig pressure conditions.	Crew Systems Division reach measuring device. (Suit ventilation and pressurization equipment were used to provide the proper vent flow and suit pressures during testing.)

Angular-range study. - This study used the new mobility-notation system.* Wearing the LCG, the test subject was appropriately positioned and restrained on the mobility-notation table, and the angular excursion for the following movements were obtained for the unsuited, vented, and pressurized (3.7 psig) conditions:

1. Forearm, supination-pronation
2. Wrist, flexion-extension
3. Hip, adduction-abduction
4. Hip, flexion-extension
5. Shoulder, flexion-extension
6. Shoulder, frontal plane, adduction-abduction
7. Shoulder rotation
8. Elbow, flexion-extension
9. Wrist-forearm, flexion-extension
10. Hip, rotation
11. Ankle, flexion-extension
12. Trunk, rotation
13. Shoulder, transverse plane, adduction-abduction
14. Knee, flexion-extension
15. Foot, flexion
16. Trunk-hip, flexion-extension
17. Trunk-hip, lateral flexion

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*This system was developed by Dr. S. Schwartz, Grumman Aircraft Engineering Corp., Mr. J. Roebuck, North American Aviation, Inc., and Mr. J. C. Hardy, Hamilton Standard Division of United Aircraft, in cooperation with NASA.

Strobe and movie sequences study. - This series of multiexposure photographs and movies was taken for the pressurized subject, wearing the suit C LCG under all suits. The series of movements was photographed with and without the TMG. Suit A did not have its own TMG; so, for this film study, the subject donned the TMG top of suit C and the TMG trousers of suit B. A series of movements was performed before a vertical grid board with the subject's heels 33 inches from the board, and with the camera lens 63 inches from the floor and 12 feet from the subject.

Test procedures. - For the angular-range study, angles were measured directly and comparisons made for the three suits and for the various test conditions. * This procedure provided an indicator of relative mobility for the suits. For the movements considered, judgments were also made concerning the relative capability of the suits to meet mission requirements.

For the strobe and cine evaluations of general mobility, comparisons were made from the direct comparisons of mobility limits before the grid board. The suits were rated along a continuum representing their capability for providing adequate mission mobility relative to the movements under evaluation.

Data for angular-range study. - Results of the angular-range study are shown in table XI. The summary in table XII was obtained by assigning points on a competitive basis, by using the weights for each motion as presented in column 2 of table XI, and by using measurements in the nude as a baseline. Using these data, the space suits were rated as follows.

1. Vented condition. Suit C ranked first, suit A second, and suit B third.

2. Pressurized to 3.7 psig. Suit A ranked first, suit C second, and suit B third.

3. In a final rating for the angular-range study, suit C ranked first, suit A second, and suit B third.

Data for strobe and movie sequences. - After studying the strobe series and viewing the movies of mobility sequences, the three space suits were rated by the evaluation team. For the 3.7 psig condition, with and without the TMG, suit A was ranked first, suit C second, and suit B third.

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*Analysis was carried out by Dr. S. Schwartz, Grumman Aircraft Engineering Corp.

TABLE XI. - SUMMARY OF MOBILITY TABLE ANALYSIS

Movement (a)	Weight factor	Nude baseline, deg	Angles of excursion						Percent of motion: nude to vent and vent to 3.7 psig					
			Suit C		Suit A		Suit B		Suit C		Suit A		Suit B	
			Vent	3.7 psig	Vent	3.7 psig	Vent	3.7 psig	N to V (b)	V to P (c)	N to V (b)	V to P (c)	N to V (b)	V to P (c)
1	3	180	194	175	168	179	180	180	100	90	93	100	100	100
2	3	160	178	132	140	125	146	132	100	74	87.5	89	91	90
3	7	180	41	32	35	15	40	35	23	78	19.4	43	22	87.5
4	8	120	90	40	80	65	70	62	75	45	67	81	58	89
5	8	250	216	190	182	168	160	139	86.5	88	73	92	64	87
6	8	155	115	95	125	117	80	86	74	83	81	94	52	100
7	6	160	170	204	185	165	164	150	100	100	100	89	100	91
8	6	150	167	106	162	150	145	127	100	63	100	93	97	88
9	3	120	125	112	105	89	98	105	100	90	87.5	85	82	100
10	5	133	130	101	125	106	126	78	98	78	94	85	95	62
11	4	78	79	82	70	56	68	70	100	100	90	80	87	100
12	2	100	70		60		48		70		60		48	
13	8	193	168	121	112	102	118	132	87	72	58	91	61	100
14	6	140	160	125	143	145	135	130	100	78	100	100	96.5	96
15	2	43	53						100					
16	3	68	80		44		54		100		65		79	
17	3	78	50		32		16		64		41		21	

[a]Seventeen movements are described in the paragraph entitled "Angular range study."

[b]Nude measures compared with vent measures.

[c]Vent measures compared with pressurized measures.

TABLE XII. - SUMMARY OF MOBILITY POINTS (WEIGHTED)

Percent of weighted mobility points compared with current suit technology. Best suit = 100 percent.			
	Suit C	Suit A	Suit B
Vented	95	67	52
Pressurized	72	77	68
Percent of weighted mobility points compared with nude range. No restriction = 100 percent.			
	Suit C	Suit A	Suit B
Vented	82	63	53
Pressurized	58	62	57

Final general mobility rating. - The two evaluations (angular-range study along with the strobe and movie sequences) were considered together in arriving at a final rating on general mobility. Since the strobe and cine sequences included a broader range of mission-related movements, this portion of the test received a weight of 2. In the final rating on general mobility, suit A placed first, suit C second, and suit B third.

Analysis. - Suit C scored highest on the vent conditions for the mobility table, and suit A scored highest on the pressurized runs. Suit B was consistently low in the analysis. For the pressurized runs on the mobility table, suit A scored high on factors such as hip flexion-extension but low on hip adduction-abduction. Suit A also scored high on elbow flexion-extension, hip rotation, and knee flexion-extension; but it scored low on wrist-forearm flexion-extension, ankle mobility, and shoulder movement in the transverse plane.

For the strobe and cine sequences, suit A showed a clear superiority over the other two suits for pressurized mobility, both with and without the TMG. The arm and shoulder mobility was particularly good; and the subject could hold his hands over his head, relaxing and allowing his arms to remain elevated without having to fight a severe torque to keep them there. Hip flexion was also particularly good, for the pressurized subject could raise his leg more than 18 to 20 inches without leaning back and swinging around sideways to carry out the maneuver as was necessary in the other two suits. A factor of considerable significance was the ease and smoothness of motion carried out with suit A during pressurized mobility. The other two suits did not allow this ease of motion.

The mobility concepts manifested in suit A have the most developmental impact. However, it would appear that an ankle joint would add much to walking, and an improvement in wrist stability and mobility is certainly needed. In addition, a method of allowing torso-bending should be investigated. Another factor to be considered is the improvement in pressurized shoulder mobility brought about by the suit C TMG top. An increase of 54° in shoulder flexion-extension and an increase of 62° in shoulder rotation were noted when data were compared with the suit B TMG top. While there is a great deal of improvement to be made in the area of pressurized mobility in the TMG, it is noted that this concept has a great deal to offer, and it is recommended that further developmental study be carried out to improve the concept.

X-ray Study of Eye-Heart Angle and Joint Interface

Test procedure. - Test subjects were volunteer army officers who were carefully selected to match the critical dimensions of the test subject used throughout the test program. For comparison purposes, measures of eye-heart angle and suit-joint mobility were obtained for subjects in both the nude condition and in the suited, pressurized condition. For the eye-heart angle study, the subjects were placed in the mockup, left couch, and were appropriately restrained.

Angles were measured directly, using as reference lines the midshaft of the major bones involved in joint movements. The eye-heart angle was measured by using procedures established by the medical staff. * Since the eye-heart angle was the most critical aspect of the study, this section of the analysis was weighted 2, and the angular decrement and suit-joint interface phase of the analysis was weighted 1.

Analysis. - When the test subjects were nude and when suited and pressurized at 3.7 psig, the eye-heart angles were as follows.

Angle	Suit B, degree	Suit C, degree	Suit A, degree
Nude	7.5	8	8
3.7 psig	8	23.5	19

For the eye-heart angles, ratings placed suit B first, suit A second, and suit C third. Rating for suit C was zero, and there was a large difference between the first-place suit B and suit A. The pressurized suit B met all requirements, while suit C at 3.7 psig was beyond the acceptable limit of 18°. The eye-heart angle for suit A was 19° for the pressurized state, which was marginal and thus rated "highly questionable." While the eye-heart angle for the vented condition was not measured in this study, it should be noted that the 10-g centrifuge run failed to produce any "gray-out" or loss of peripheral vision for suits B and C. Since suit C represented an extreme in the eye-heart angle considered in this evaluation (due to neck design), it can be concluded that the eye-heart angle for suit A in the vented condition is also within acceptable limits.

*Dr. Zoltan Petrany and Dr. V. P. Collins of the Baylor University College of Medicine, Houston, Texas, served as radiology consultants for the study.

In the study of joint mobility and suit-joint interface, suit A caused the least degradation in joint mobility. Suits B and C were approximately equivalent in this function. Angular data are presented in table XIII. For this joint-mobility study, suit A rated first, with both suit B and suit C rating in second place.

In a final rating (including both the eye-heart angle study and suit-joint mobility study), suit B rated in first place, suit A in second, and suit C in third.

The eye-heart angle of suit B (pressurized) was clearly superior to that of the other two suits. All suits were well within requirements for the eye-heart angle in the vented condition. The suit-joint mobility degradation of suit A was significantly less than that for the other two suits. The helmets of suits A and C need to be relocated to provide the appropriate eye-heart angle for the pressurized state. As they are now, these two suits tend to project too far forward from the longitudinal centerline, thus increasing the eye-heart angle.

Maximum Visual Field

Test procedure. - The following procedure was used in positioning the subject and the helmet in relation to the optical perimeter.

1. The test helmet was rotated on the neck ring to aline the helmet center mark with the neck ring center mark.

2. The subject's head was then positioned inside the helmet to aline the head longitudinal center line with the helmet and neck ring center marks.

3. The complete system (head and helmet) was then positioned with the center of the subject's eye pupil normal to both the 90° and the 0° positions on the optical perimeter.

4. The helmet neck ring angle with the horizontal was positioned according to manufacturer's specifications.

After completing this zeroing procedure, the helmet was secured in this zero position. During the test, the subject was allowed complete freedom of movement in the helmet, since the objective of the test was to ascertain the visual-field capabilities of each helmet as opposed to the subject's visual-field capabilities.

TABLE XIII. - ANGULAR DATA FOR JOINT MOBILITY AND SUIT-JOINT INTERFACE

Movement	Suit C				Suit A				Suit B			
	Nude	3.7 psig	Diff.	Percent at 3.7 (a)	Nude	3.7 psig	Diff.	Percent at 3.7 (a)	Nude	3.7 psig	Diff.	Percent at 3.7 (a)
Wrist Adduction	37	24	13	64.8	34	34	0	100	30	24	6	80.0
Abduction[b]	40	48	-8	120	34	42	-8	123.5	35	30	5	85.6
Dorsiflexion	62	56	6	90.3	63	57	7	90.4	75	68	7	90.6
Palmar flexion	87	68	19	78	60	56	4	93.3	70	53	17	75.7
Elbow Flexion	152	122	30	80.2	153	137	16	89.5	151	122	29	80.8
Extension[c]	--	--	--	--	0	5	-5		7	11	-4	157.0
Shoulder Neutral lateral	0	-10	-10		-4	-7	3		-18			
Neutral (front view)	11	39	28	35.5	4	20	16			35		
Abduction	158	83	75	52.5	167	125	42	74.8	146	78	68	53.4
Flexion	163	92	61	56.4	189	136	53	71.9	145	63	82	43.4
Extension	66	65	1	98.4	83	47	36	56.6	59			
Hip Flexion	99	57	42	57.5	123	55	68	44.7	114	58	56	50.9
Knee Neutral position	-4	-2	2	50	-2	20	22		3	3	0	100
Flexion[c]	130	93	37	71.5	96	--	--	--	95	87	8	91.5

[a]Percent of motion retained in the pressurized state (percent of nude).

[b]This measure will be repeated at a later date.

[c]This measure is, as yet, incomplete.

Subsequent to the test, the subject was instructed to indicate the point at which he could no longer see the target as it was moved on the perimeter arm from directly in front (0°) to directly behind (180°) him. This procedure was followed for each angular increment of the perimeter arm, with four readings taken at each increment.

Two additional measures were used to determine the downward and upward "operational" visual capabilities of each suit. These measures were taken with the subject standing and zeroed under the perimeter. To determine upward visual capabilities, the subject was instructed to follow the target on the perimeter arm as it was moved directly over him (the subject was allowed to bend his torso). To determine downward visual capabilities, the same test configuration was used; that is, the subject was standing and zeroed under the perimeter, but was allowed to bend his torso. The subject was instructed to indicate the highest point on his suit that he could see. A line from this point on the suit through the center of the eye pupil to the perimeter arm was then constructed to determine the downward visual angle measured from the horizontal.

All of the above measures were taken under two conditions, pressurized (3.7 psig) and vented. To control test-subject variability, the same test subject was used throughout the visual-field test.

Analysis. - The mean value of the four trials for each angular increment of the perimeter was computed, and these data are shown in tables XIV and XV. Figures 8 through 12 show the same data graphically in polar coordinates of the subject's binocular visual field for each suit. Table XVI shows upward, downward, and lateral visual-field capabilities for each suit compared with specifications. Table XVII shows the visual capability of the suited subject relative to the visual capability of the nude subject.

In the final rating, suit A rated first, suit C second, and suit B third. Under static and operational conditions, suit A provided evidence of superior visual-field capabilities. It should be pointed out that there was little difference between suit A and suit C, but there was a significant difference between these two suits and suit B which rated third.

Upward visual-field restrictions in both suit A and suit C are intensified because the helmet of each suit is positioned in front of the suit longitudinal center line. This position limits the upward visual capabilities because ventrodorsal (backward) movement of the subject's head is restricted in each helmet. This helmet configuration also increases the eye-heart angle of both suit A and suit C.

TABLE XIV. - SUIT VISUAL CAPABILITIES BY ANGULAR INCREMENT (SUIT VENTED)

(a) Visual capabilities to right

Angle increment	0	10	20	30	40	50	60	70	80	90	100	110	120	150
Suit B	76.3	77	81	89.3	95.5	106.5	123.3	124.3	124.8	125	128.5	112	115.3	89.8
Suit A	80.8	88.8	88.5	89	180	180	180	180	180	180	180	180	180	180
Suit C	84	91.3	180	180	180	180	180	180	180	180	180	180	180	180

(b) Visual capabilities to left

Angle increment	0	10	20	30	40	50	60	70	80	90	100	110	120	150
Suit B		77	79.8	86.5	94	102.5	108	115	115	120.8	119.3	116	111.5	91
Suit A		86.8	95.5	153.3	166	167	170	172	175	175	175	175	175	175
Suit C		96	180	180	180	180	180	180	180	180	180	180	180	180

TABLE XV. - SUIT VISUAL CAPABILITIES BY ANGULAR INCREMENT (PRESSURIZED)

(a) Visual capabilities to right

Angle increment	0	10	20	30	40	50	60	70	80	90	100	110	120	150
Suit B	77.8	83.8	90	94	102.3	114.8	119.8	124.5	127	126.3	121.8	121.8	117	102.3
Suit A	87.3	78.8	87	180	180	180	180	180	180	180	180	180	180	180
Suit C	82.8	85.3	91.8	180	180	180	180	180	180	180	180	180	180	180

(b) Visual capabilities to left

Angle increment	0	10	20	30	40	50	60	70	80	90	100	110	120	150
Suit B		86	89	87.5	96	104.5	114.3	120	121.3	122.8	121.3	119.8	116.3	112
Suit A		87	88.5	162.5	172	175	175	175	175	175	175	175	175	175
Suit C		94.3	180	180	180	180	180	180	180	180	180	180	180	180

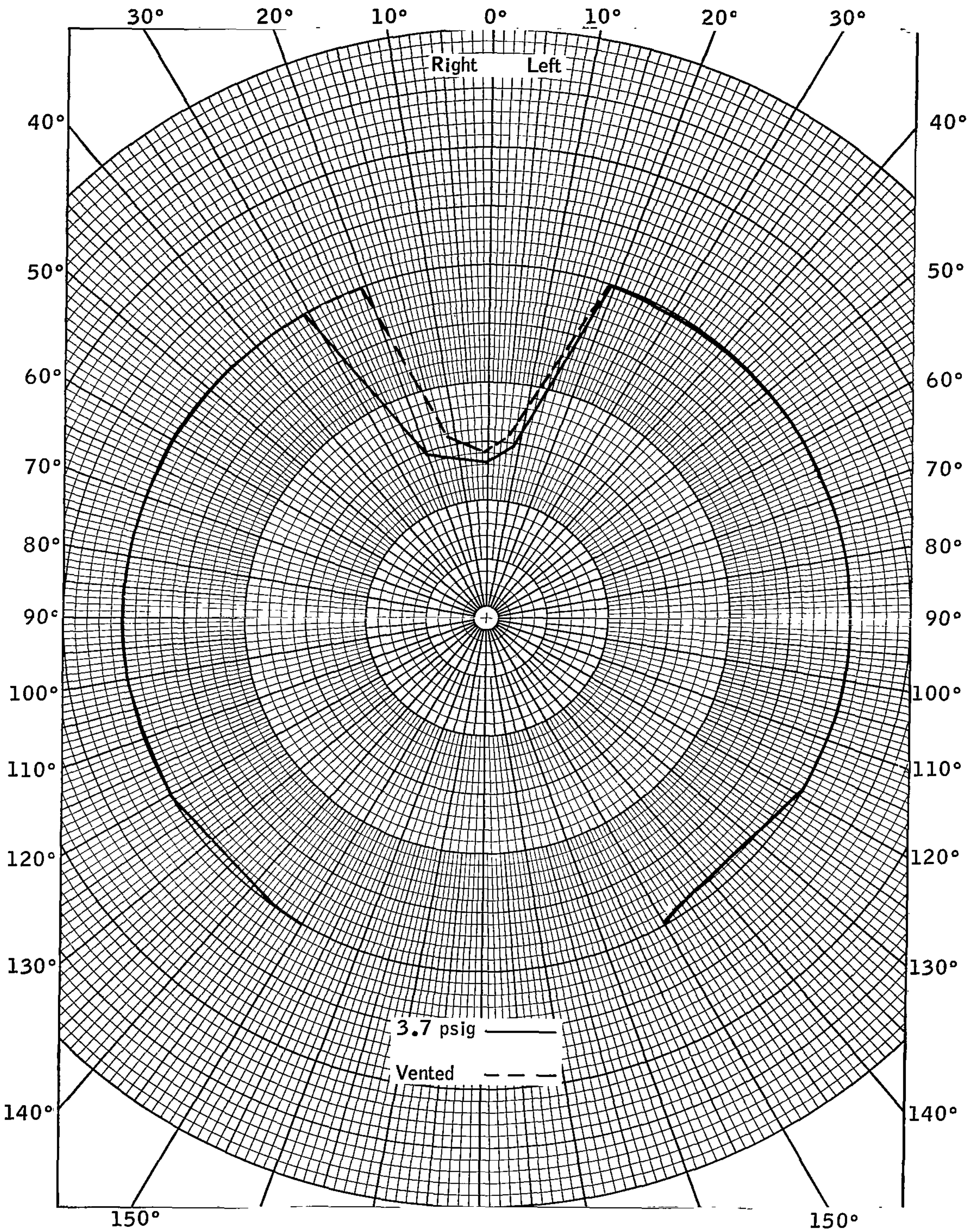

Figure 8. - Visual-field capability for space suit C.

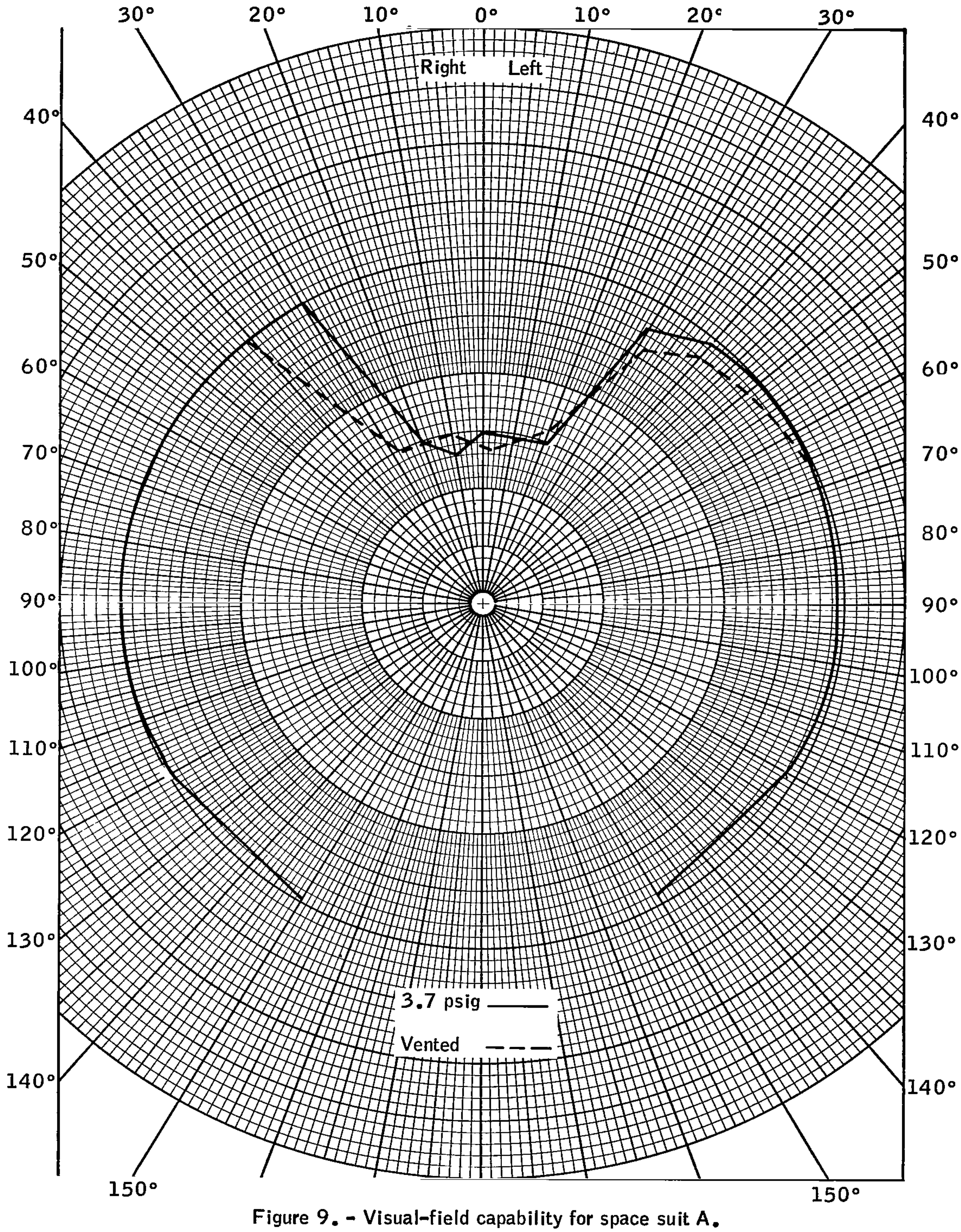

Figure 9. - Visual-field capability for space suit A.

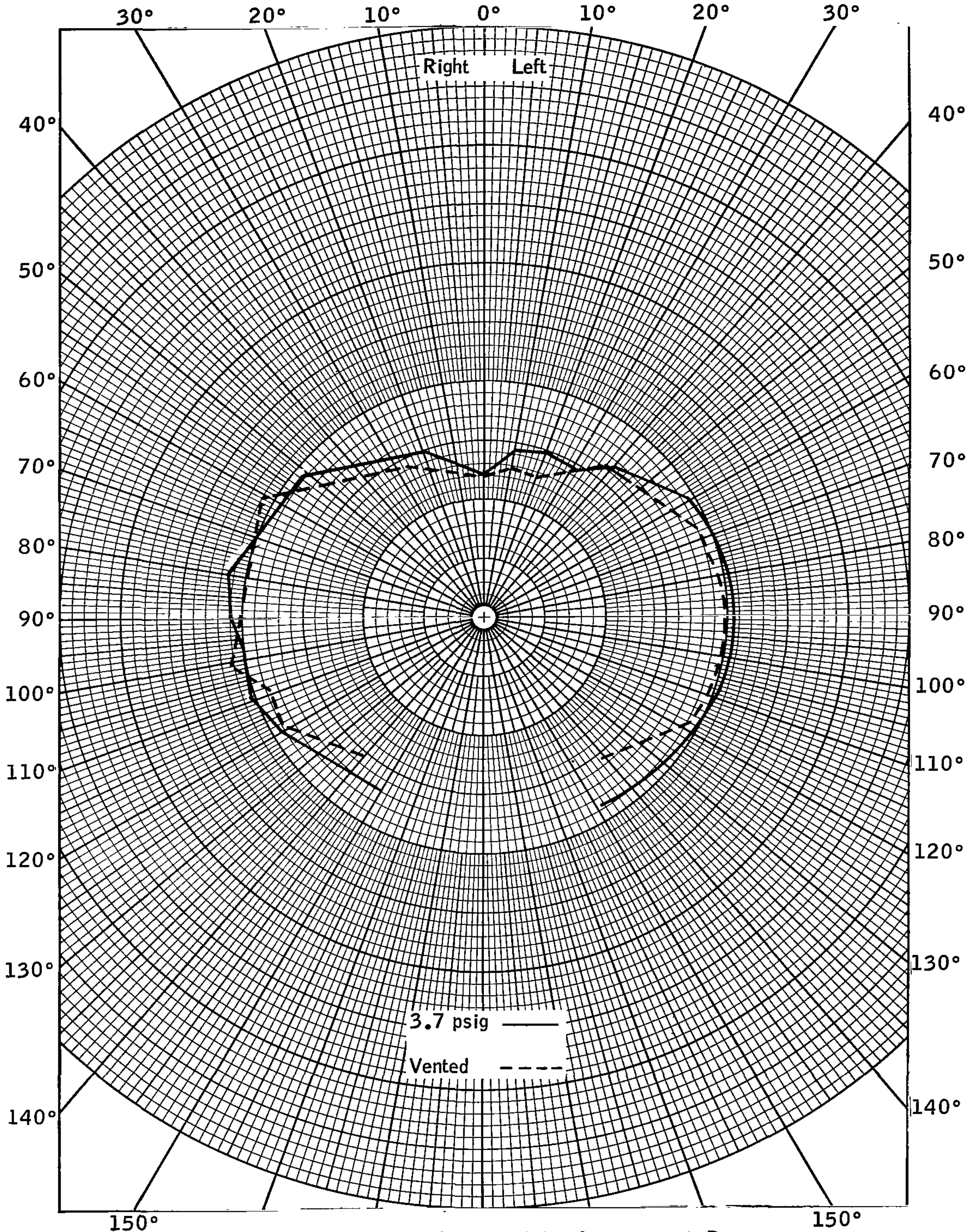

Figure 10. - Visual-field capability for space suit B.

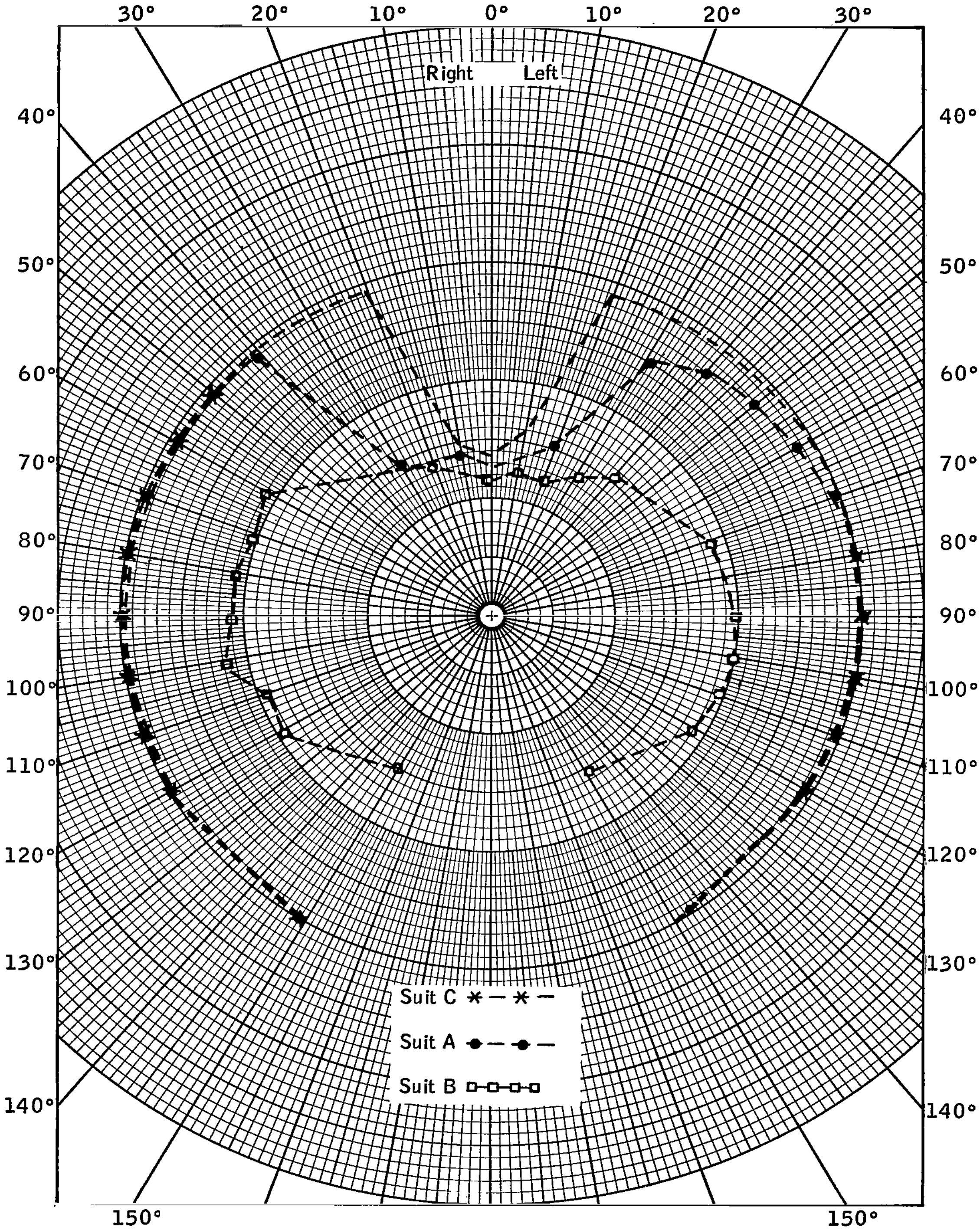

Figure 11. - Visual-field capability, vented condition.

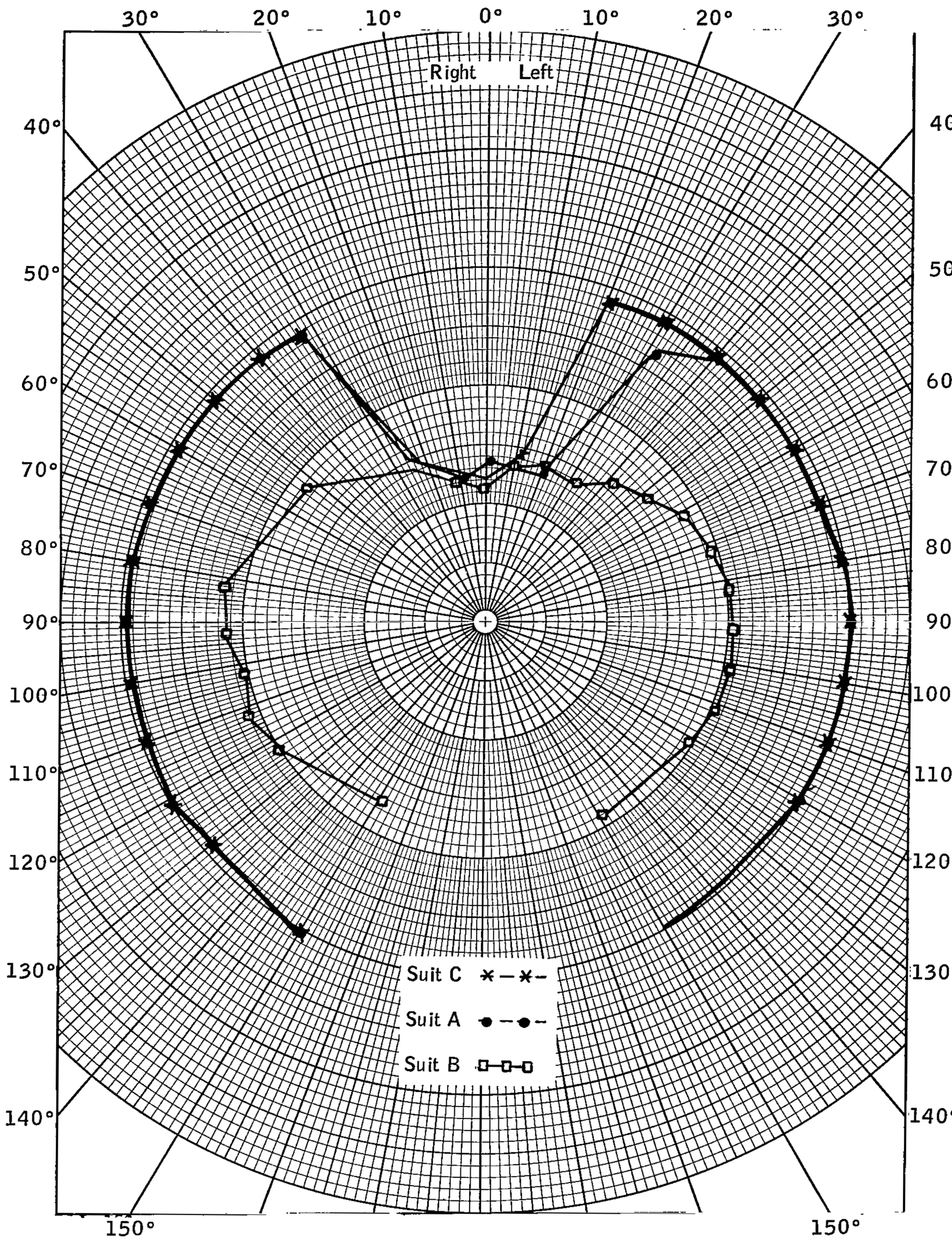

Figure 12. - Visual-field capability, pressurized condition.

TABLE XVI. - SUIT VISUAL CAPABILITIES - UP, DOWN, AND LATERAL

		Suit B, visual angle, degrees	Percent of specification (a)	Suit C, visual angle, degrees	Percent of specification (a)	Suit A, visual angle, degrees	Percent of specification (a)
UP,[b]	Vented,	120	133	118	131	140	155
	3.7 psig	110	122	115	127	105	116
DOWN,[b]	Vented,	96	91	95	90	97	92
	3.7 psig	91	87	95	90	95	90
LATERAL,	Vented,	245.8	102	360	150	355	148
	3.7 psig	249.1	104	360	150	355	148

[a]Specification: Up 90°; Down 105°; Lateral 240°.

[b]Operational measurements.

TABLE XVII. - RELATIVE VISUAL CAPABILITIES BETWEEN SUITED AND NUDE TEST SUBJECT

(a) Suit pressurized to 3. 7 psig

3. 7 psig	Right*	Left*	Total*	Percent
Suit B	1523. 20	1410. 80	2934. 00	60. 37
Suit A	2233. 10	2085. 00	4318. 10	88. 84
Suit C	2239. 90	2254. 30	4494. 20	92. 47
Nude subject	2520. 00	2340. 00	4860. 00	100. 00

(b) Suit vented, 0. 18 psig

Vented	Right*	Left*	Total*	Percent
Suit B	1468. 60	1336. 40	2805. 00	57. 71
Suit A	2147. 10	2060. 60	4207. 70	86. 57
Suit C	2335. 30	2256. 00	4591. 30	94. 47
Nude subject	2520. 00	2340. 00	4591. 30	100. 00

*Right, left, and total refer to a summation of visual capability (in degrees) at each perimeter test increment.

Suit A is superior in downward and upward visual capabilities, when the pressurized and vented conditions are considered as a single unit of interest rather than being considered separately. Operationally, this is a valid conclusion. It should be noted, however, that insofar as operational downward vision is concerned, each suit possesses the capability for the subject to see his respective gas connectors.

Left visual-field restrictions for the suit A helmet are due to asymmetry of the helmet exterior painting rather than to any structural defect.

It is recommended that the helmet of suit A be repositioned to a configuration more congruent with suit centering, thereby eliminating downward visual and eye-heart angle disadvantages. It is also recommended that the possibilities of a totally transparent helmet shell be explored to allow maximum visual field.

Hand Dexterity

Test procedure. - The Purdue Pegboard Test was administered to the suited test subject in the vented and pressurized (3.7 psig) suit conditions. During two sessions of testing, six trials per suit were given for each of the two suit conditions. The test conductor turned the pegboard 180° for all trials so that wrist and finger mobility, rather than arm-reach mobility, was the influential factor. The subject was also given six trials of the test while he was barehanded, and these data were considered to represent optimal performance.

Analysis. - Table XVIII shows a comparison between barehand (optimal = 100 percent) performance and the performance retained with each suit under each condition. The fourth column of this table is the combined score of the three preceding test sequences in which pins only were used. This comparison shows clear differences in the performances of the three suits, and these differences were analyzed by the Kruskal-Wallis one-way analysis of variance. Analysis of the four parts of the pegboard test, shown in table XIX, indicates that the difference was significant at 0.01 level in all cases except in the left-hand and both-hands test sequences under the vented condition. The both-hands test was significant at the 0.05 level, and the left-hand test was significant at the 0.10 level. Thus, the observed differences in manual dexterity can be treated as a "real difference."

Ratings placed suit A in first place, suit B in second, and suit C in third. Suit C allowed considerably less wrist and finger dexterity than either of the other suits.

TABLE XVIII. - BAREHAND SUMS COMPARED WITH SUITED RAW SCORE SUMS

	Right hand		Left hand		Both hands		Sum of scores on all hands		Assembly	
	Score	Percent (a)	Score	Percent (a)	Score	Percent (a)	Score	Percent (a)	Score	Percent (a)
Barehanded (Optimal performance)	108	100	111	100	80	100	299	100	253	100
Vented										
Suit C	68	62.96	66	59.46	45.5	56.88	179.5	60.03	106	41.90
Suit B	76	70.37	78	70.27	52	65.00	206	68.90	133	52.57
Suit A	75	69.44	75	67.57	55	68.75	205	68.56	146	57.71
Pressurized										
Suit C	33	30.56	36	32.43	18	22.50	87	29.10	45	17.79
Suit B	49	45.37	49	44.14	32.5	40.63	130.5	43.65	79	31.23
Suit A	57	52.78	48	43.24	33.5	41.88	138.5	46.32	82	32.41

[a]Percent of performance retained.

TABLE XIX. - KRUSKAL-WALLIS ONE-WAY ANALYSIS OF VARIANCE[a]

Pressurized	H score obtained	0.05 significance level		0.01 significance level	
		H score required	Significant	H score required	Significant
Right hand	12.2349	5.99	Yes	9.21	Yes
Left hand	10.2647	5.99	Yes	9.21	Yes
Both hands	11.4701	5.99	Yes	9.21	Yes
Assembly	11.7249	5.99	Yes	9.21	Yes
Vented					
Right hand	12.7654	5.99	Yes	9.21	Yes
Left hand	5.6648	5.99	No	9.21	No
Both hands	8.2395	5.99	Yes	9.21	No
Assembly	10.7396	5.99	Yes	9.21	Yes

[a]For a description of the Kruskal-Wallis one-way analysis of variance, see Siegel, Sidney: Nonparametric Statistics for the Behavioral Sciences. McGraw-Hill Book Co., Inc., 1956, pp. 184-193.

The reduction in dexterity from the barehand level, a reduction applying to all the suits, had several causes. Fingertip lights were detrimental, especially in suit C. Also, the gloves of suit C were the thickest and most cumbersome. On this suit, the wire fingernails in the thumb of the left glove came loose and interfered with test performance, and the gloves cut the subject's knuckles.

Since fingertip lights interfered with hand dexterity, it is recommended that the placement of these lights be improved. The concept of fingernails on the gloves appears worthy and should be developed further, but definite improvement is necessary because the fingernails on the gloves of suit C became bent and actually interfered with dexterity. Another factor needing further development is the thickness of the material encasing the fingers. The thin material used in the gloves of suits A and B showed definite advantages over the thick material in the fingers of suit C.

Placement of the palm-restraint device should be optimized in order to allow the hand to bend below the knuckles. If the restraint device is too high and near the fingers, the subject is unable to grasp and can only flex the upper part of the fingers. Wrist stability should also be improved in all gloves, especially in the gloves of suits A and C.

All of the gloves produced pressure points at the base of the thumb and on top of the hand. These pressure points brought about excessive tiring of the hand and forearm, and induced cramping in the thumb and forearm. Consequently, considerable developmental work is needed to improve the gloves, because none of these gloves would meet the multiplicity of requirements involved in long-term pressurized wear.

Functional Reach

Test procedure. - The reach-measuring device of the MSC Crew Systems Division was used as a means of obtaining objective data for this study. The test subject, in his shirtsleeves, was placed in the seat of the reach-measuring device and restrained with a lap belt and chest strap. The seat was then adjusted so that the pivot axis of the subject's shoulders was located on the horizontal axis normal to the focus of the measuring rods. The limits of functional reach were measured in 15° increments along the semicircular protractor head. These measures were repeated at 15° increments as the protractor head was rotated through a 90° arc to a horizontal position and at 30° and 60° increments below the horizontal plane. Three trials were made in a shirtsleeve condition to establish a baseline reference. This test procedure was followed for each of the three suits which were tested under both the vented and pressurized conditions. At each of these conditions, two trials were made for each suit. Throughout the test, the seat location was maintained at the reference position established when the subject was in his shirtsleeves. Figure 13 illustrates the planes on which the measurements were taken.

Analysis. - Tables XX through XXVI show the mean values which were computed from each set of measured values. These data were also plotted on polar coordinate paper and are presented in figures C-1 through C-18 of appendix C. At the specified position of the protractor head, each figure represents a plot of the mean values for the three suits and the shirtsleeve baseline values. These values also may be found in the tables by reading across the columns of the tabulated data for the given horizontal position.

The functional reach of the three suits was rated on the basis of the data described above. Primary consideration was given to the subject's reach-capability ventral of the mid-transverse plane. There are few, if any, requirements for maximum functional reach in the dorsal direction. Using the rating scale, suit A was rated in first place, suit B in second, and suit C in third. None of the suits was rated as meeting all requirements because the operational-reach requirements for all possible contingencies, both intravehicular and extravehicular, cannot be clearly defined.

For test trials in the vented condition, there was very little difference in the data obtained for the three suits. On the basis of these data, it would have been very difficult to rate one suit above another. In the pressurized trials, however, the data clearly showed suit A to be superior to both of the other suits at nearly all of the measured points. In addition, in the extreme angles (that is, 15° horizontal, 90° vertical) the subject demonstrated his ability to maintain the position over longer periods of time in suit A. This fact can be important if there are requirements to perform discrete adjustment tasks such as operating a thumb-wheel.

During the first pressurized trial in suit C, the subject noted a major pressure point slightly below the left pectoralis major as a result of the inside water connector. This portion of the connector was removed for the second trial, and the pressure point was relieved. Careful attention must be given to the design and location of all fittings (water, gas, and electrical connectors, restraint cables, vent ducts, and zippers) to prevent such pressure points and to insure that they do not contribute to the mobility decrement which is inherent in pressure suits.

In general, studies should be continued in an effort to refine the shoulder and elbow joints to provide maximum range of motion with minimum torque requirements.

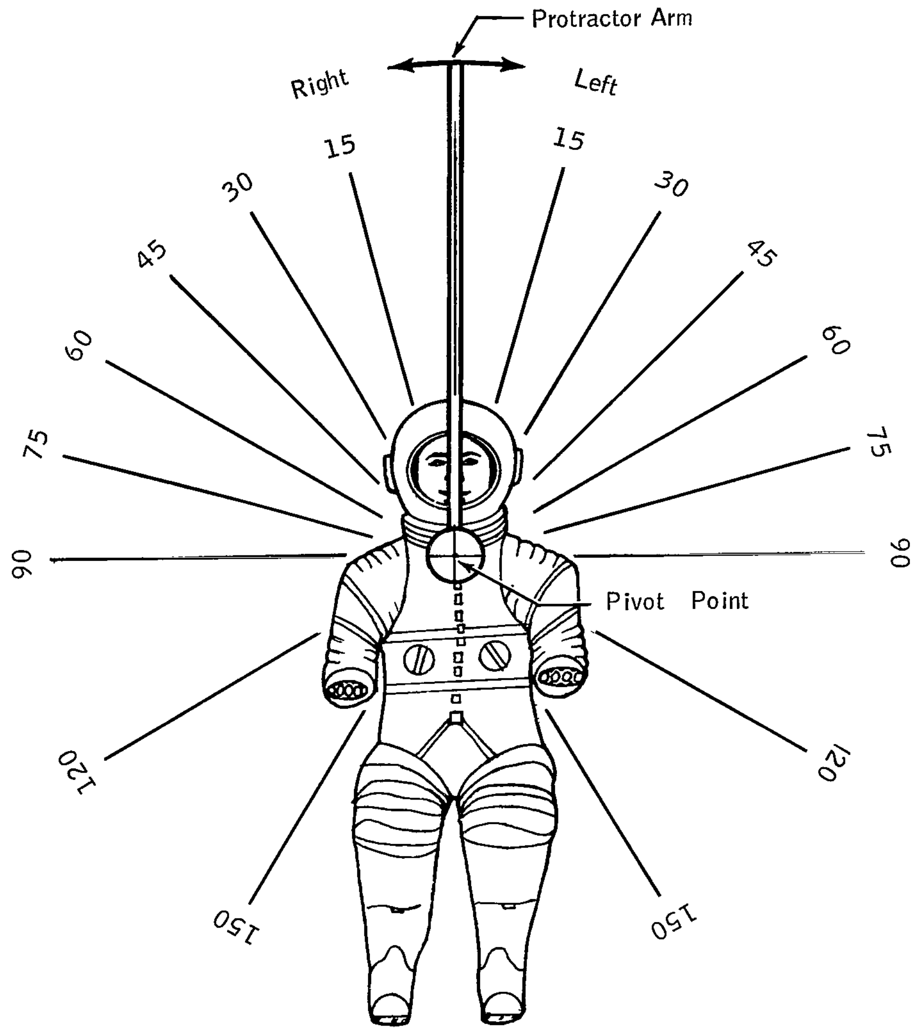

Figure 13. - Illustration of reach-measurement device.

TABLE XX. - FUNCTIONAL REACH IN SHIRTSLEEVES

(a) Means of measurements to the left

Horizontal \ Vertical	0	15	30	45	60	75	90	105	120
0	26.50	25.67	24.67	23.92	23.42	23.42	22.92	22.17	*21.00
15	26.42	25.92	25.58	25.00	24.83	24.75	24.50	24.08	*22.00
30	26.42	26.92	26.50	26.25	25.92	25.67	25.75	25.58	22.42
45	26.42	27.17	27.33	27.17	27.17	26.92	26.92	26.83	25.08
60	26.92	27.00	27.33	27.83	28.00	27.67	27.67	27.08	25.83
75	26.50	27.67	28.00	28.67	28.67	28.58	28.67	28.00	26.33
90	27.00	28.25	29.33	29.75	29.50	29.33	29.17	28.58	26.92
120	26.75	28.33	28.75	29.42	29.33	29.42	28.75	28.58	27.33
150	26.58	27.50	27.92	28.08	28.42	28.08	27.75	27.00	25.75

(b) Means of measurements to the right

Horizontal \ Vertical	0	15	30	45	60	75	90	105	120
0	26.40	25.58	24.66	24.25	24.58	23.33	23.16	23.00	*23.12
15	26.91	26.50	26.16	25.66	24.91	24.75	24.75	24.83	*25.00
30	27.08	27.16	27.16	26.75	26.75	26.50	26.33	26.50	25.41
45	26.75	27.00	27.75	27.58	27.66	27.83	27.33	27.75	26.08
60	26.75	27.83	27.91	28.66	28.75	28.41	28.58	28.66	27.58
75	27.16	28.50	29.25	29.50	29.66	29.75	29.08	28.33	27.41
90	26.58	28.50	29.33	30.00	30.16	30.16	29.91	29.58	28.50
120	27.16	28.75	29.41	29.91	30.58	30.08	29.50	28.83	27.66
150	27.25	28.16	28.50	28.83	28.83	28.75	28.41	28.08	26.25

*Only two measures available instead of three.

TABLE XXI. - FUNCTIONAL REACH IN SUIT C, VENTED

(a) *Means of measurements to the left*

		Vertical								
		0	15	30	45	60	75	90	105	120
Horizontal	0	24.5	23.5	22.62	21.12	20.12	18.62	16.5	12.75	
	15	24.0	23.62	23.0	22.50	22.0	21.62	19.38	15.88	
	30	24.0	24.0	23.88	23.88	23.62	23.12	22.12	17.5	
	45	24.12	24.75	24.75	25.0	25.12	25.0	23.25	20.66	
	60	24.38	24.75	25.75	26.25	26.25	26.0	24.88	23.25	
	75	24.38	25.75	26.88	27.88	28.25	27.62	27.75	26.12	
	90	24.88	26.0	27.12	29.0	29.25	29.5	29.0	27.75	25.38
	120	23.75	25.88	27.88	29.12	29.75	30.0	29.25	28.5	26.5
	150	24.0	25.75	26.88	27.75	28.0	27.75	27.25	26.75	25.0

(b) Means of measurements to the right

		Vertical								
		0	15	30	45	60	75	90	105	120
Horizontal	0	24.38	23.12	21.25	19.62	17.88	16.88	14.75	12.0	
	15	24.50	23.5	22.12	21.62	20.62	19.75	17.62	16.25	
	30	24.66	24.62	24.0	23.50	23.50	22.62	21.62	19.62	14.75
	45	24.88	25.0	24.88	24.62	24.75	24.75	24.12	22.62	19.0
	60	24.62	25.5	25.62	26.12	26.62	26.38	26.0	25.25	22.12
	75	24.75	26.0	27.0	27.62	28.5	28.38	28.12	27.12	*25.00
	90	24.62	26.75	27.5	28.5	29.12	29.0	28.62	27.88	25.62
	120	24.62	26.38	27.62	29.12	29.62	29.38	29.0	28.25	26.88
	150	24.25	26.0	27.88	28.0	28.62	27.75	27.25	26.75	25.00

*Only two measures available instead of three.

TABLE XXII. - FUNCTIONAL REACH IN SUIT C, PRESSURIZED

(a) Means of measurements to the left

Horizontal	Vertical 0	15	30	45	60	75	90	105	120
0	21.25	20.00	18.25	16.50	14.75				
15	20.88	20.62	20.50	19.88	19.00	16.00			
30	21.13	22.13	22.12	22.0	21.00	18.50			
45	21.13	22.38	23.75	24.0	24.62	23.25	17.88		
60	20.88	22.50	24.38	25.38	26.12	25.50			
75	21.13	22.50	24.75	26.50	27.12	27.50	26.62		
90	20.88	23.50	25.50	27.25	28.62	28.88	28.25	26.62	
120	20.88	23.25	25.25	27.25	28.25	28.62	28.00	26.62	*25.00
150	20.88	22.38	23.62	25.50	25.38	25.62	25.12	24.74	*24.50

(b) Means of measurements to the right

Horizontal	Vertical 0	15	30	45	60	75	90	105	120
0	19.25	17.75	16.12	14.88					
15	19.25	19.00	18.25	17.25	15.50				
30	19.50	20.12	20.12	20.00	19.25	17.25			
45	19.50	21.25	22.12	22.62	22.25	21.88	19.50		
60	19.62	21.75	23.62	24.62	25.12	25.12	24.12		
75	20.12	23.00	24.62	25.88	27.62	27.75	27.25	*26.00	
90	19.75	22.62	25.38	27.12	28.88	29.25	29.00	27.38	
120	19.88	23.00	25.12	27.12	28.62	29.12	29.12	28.00	
150	19.75	23.00	24.38	25.50	26.11	25.62	26.00	25.50	

*Only one measure available instead of two.

TABLE XXIII.- FUNCTIONAL REACH IN SUIT A, VENTED

(a) Means of measurements to the left

		Vertical								
		0	15	30	45	60	75	90	105	120
Horizontal	0	24.50	24.13	22.38	21.75	20.75	18.88	16.38		
	15	24.38	23.88	23.38	23.25	23.25	20.88	19.13	*18.25	
	30	24.63	24.75	24.25	24.38	24.13	23.38	22.38	19.13	
	45	24.88	25.13	25.13	25.38	25.50	25.00	24.00	20.88	
	60	24.38	25.13	26.13	26.75	26.75	26.50	25.63	22.38	
	75	24.63	25.63	26.63	27.75	27.75	27.50	27.13	26.00	
	90	24.25	26.00	27.25	28.50	28.75	28.63	28.25	26.75	
	120	24.38	26.38	27.75	28.88	28.88	29.00	28.50	27.38	25.50
	150	24.25	25.75	26.88	27.50	27.75	27.25	26.88	26.00	23.75

(b) Means of measurements to the right

		Vertical								
		0	15	30	45	60	75	90	105	120
Horizontal	0	23.63	23.00	22.13	21.50	20.13	18.38	18.38		
	15	24.38	23.50	23.00	22.50	21.88	21.50	19.75	*19.75	
	30	24.00	24.13	23.88	23.50	23.75	23.63	22.75	21.00	*15.50
	45	24.00	24.00	24.38	24.75	24.88	25.00	24.63	23.13	*19.75
	60	24.25	24.38	25.63	26.13	26.25	26.13	25.75	24.50	20.63
	75	24.00	25.25	26.25	26.75	27.00	27.25	26.63	25.63	20.50
	90	23.75	25.25	26.50	27.63	28.00	27.75	27.50	26.50	
	120	24.13	25.88	27.13	28.63	29.00	29.13	28.75	28.00	
	150	24.38	25.50	26.50	27.25	27.63	27.88	27.38	26.38	23.75

*Only one measure available.

TABLE XXIV. - FUNCTIONAL REACH IN SUIT A, PRESSURIZED

(a) Means of measurements to the left

Horizontal	Vertical 0	15	30	45	60	75	90	105	120
0	23.25	22.75	21.25	20.38	18.38	15.38			
15	23.38	23.38	23.13	22.75	21.62	19.38	*16.50	*12.50	
30	23.38	24.13	24.13	24.50	24.38	23.63	21.50	*14.50	
45	22.88	24.50	25.25	25.88	25.75	24.88	22.88		
60	23.50	25.13	26.00	27.00	26.88	26.25	25.13		
75	23.38	25.50	26.75	27.75	27.50	27.38	26.25		
90	23.38	25.50	27.25	28.00	28.13	27.75	26.88		
120	23.50	25.25	26.88	28.00	28.25	27.88	27.63	26.50	
150	23.25	24.88	25.50	26.00	26.00	25.75	25.13	24.38	

(b) Means of measurements to the right

Horizontal	Vertical 0	15	30	45	60	75	90	105	120
0	22.50	22.00	20.88	19.63	18.13	15.88			
15	22.38	22.88	22.75	22.50	21.63	20.50	18.75		
30	22.50	23.75	24.13	24.25	24.25	23.88	22.88	†19.25	
45	22.63	24.25	25.13	25.75	25.88	25.75	24.50	*20.25	
60	22.63	24.63	25.88	27.13	27.25	27.13	26.38		
75	23.00	25.00	26.75	28.00	28.13	28.13	27.38		
90	22.63	25.13	27.00	28.50	28.88	28.63	28.00	24.50	
120	23.00	25.38	26.88	28.38	28.88	28.88	28.38	27.25	
150	22.88	24.25	25.63	26.25	26.88	26.63	26.13	24.38	

*Only one measure instead of two.

†One of two measurements was a touch only, no control.

TABLE XXV. - FUNCTIONAL REACH IN SUIT B, VENTED

(a) Means of measurements to the left

		Vertical								
		0	15	30	45	60	75	90	105	120
Horizontal	0	24.38	23.25	21.25	19.50	18.00	15.13	*16.25		
	15	24.13	23.25	22.50	21.50	20.38	18.75	†16.25		
	30	24.13	24.00	23.75	23.75	23.38	21.75	20.13	†15.38	
	45	24.13	25.00	25.13	25.25	25.13	24.88	23.50	20.25	
	60	24.25	25.13	25.75	26.50	27.00	26.63	25.25	23.13	
	75	24.13	25.75	26.75	28.13	28.63	28.50	27.50	25.25	*20.00
	90	24.13	26.13	27.38	29.00	29.50	29.25	28.75	27.38	24.88
	120	24.13	26.50	28.13	29.38	30.13	30.25	29.63	28.25	26.63
	150	24.38	25.88	27.38	27.75	27.75	27.88	26.63	25.88	23.50

(b) Means of measurements to the right

		Vertical								
		0	15	30	45	60	75	90	105	120
Horizontal	0	24.25	23.25	21.63	20.38	18.75	17.13	*16.25		
	15	23.75	23.25	22.50	21.50	20.88	19.13	18.00	15.38	
	30	24.25	24.13	24.00	23.38	23.00	22.25	21.13	20.50	*12.25
	45	24.13	24.63	25.25	25.13	25.00	24.75	24.38	22.75	18.88
	60	24.68	25.25	25.75	26.50	26.75	26.63	26.50	24.88	21.63
	75	23.30	25.50	26.63	27.50	27.88	27.88	27.38	26.50	23.63
	90	24.06	25.88	27.13	28.25	29.13	28.75	28.13	27.88	25.25
	120	24.63	26.38	27.75	28.38	29.00	29.00	28.50	27.38	26.13
	150	24.63	26.13	26.88	27.13	27.50	27.63	26.88	25.75	*25.00

*Only one measure available instead of two.

†Touched but no control on one of two measures.

TABLE XXVI. - FUNCTIONAL REACH IN SUIT B, PRESSURIZED

(a) Means of measurements to the left

		Vertical							
		0	15	30	45	60	75	90	105
Horizontal	0	21.75	20.00	17.25	25.15	13.88			
	15	21.88	21.13	20.00	18.75	16.38	*13.25		
	30	21.63	22.13	22.00	21.75	20.63	17.50	*13.25	
	45	21.63	22.75	23.38	24.38	24.00	22.75	18.63	
	60	21.00	23.25	24.88	26.00	26.63	25.63	24.38	*17.75
	75	21.75	24.13	25.50	27.13	28.25	28.25	27.50	*25.25
	90	21.75	24.25	26.50	27.88	29.00	28.63	27.75	*26.50
	120	21.38	24.13	26.25	27.88	29.00	29.50	28.63	26.63
	150	21.50	23.63	24.75	25.63	26.50	25.88	25.00	22.63

(b) Means of measurements to the right

		Vertical							
		0	15	30	45	60	75	90	105
Horizontal	0	20.88	19.38	17.25	16.63	*14.75			
	15	21.13	21.50	21.25	20.25	19.00	16.88	*13.75	
	30	21.00	22.63	22.50	23.25	22.50	21.50	19.88	*14.25
	45	21.00	23.00	23.63	24.88	25.13	24.75	23.63	20.00
	60	21.13	23.25	24.50	25.63	26.38	27.00	26.25	23.13
	75	21.00	23.88	25.63	26.75	28.38	28.63	27.63	25.13
	90	21.00	23.63	26.00	27.75	28.88	29.13	28.50	*26.25
	120	20.88	23.88	25.63	27.25	28.50	28.50	27.75	
	150	20.88	23.13	24.75	25.13	25.63	25.00	24.13	*22.50

*Only one measure instead of two.

Results

In the basic functions test, suit A rated first in four subtests, and suit B was first in one subtest. Results of each subtest may be summarized as follows.

General mobility. - The general mobility study included the angular-range study and the strobe and movie sequences study. In the final rating, suit A placed first, suit C second, and suit B third. Suit C scored highest during the vented condition, and suit A scored highest during the pressurized runs. Suit B was consistently low in the analysis.

X-ray study of eye-heart angle and joint interface. - For the eye-heart angles, ratings placed suit B as first, suit A as second, and suit C as third. (Rating for suit C was zero.) For the pressurized condition, suit B met all requirements, while suit A had an eye-heart angle of 19° and was rated as "highly questionable." All suits were well within requirements for the eye-heart angle in the vented condition. In the study of joint mobility and suit-joint interface, suit A caused the least degradation in joint mobility.

Maximum visual field. - In the final rating, suit A rated first, suit C second, and suit B third. There was little difference between suit A and suit C, but there were significant differences between these two suits and suit B. Upward visual-field restrictions in both suits A and C are intensified because the helmet of each suit is positioned in front of the suit longitudinal center line. It is recommended that the helmet of suit A be repositioned to a configuration more congruent with suit centering.

Hand dexterity. - Results of this subtest indicate that suit A allowed the most manual dexterity, followed by suit B in second place, and suit C in third place. All three of the suits showed a reduction in hand dexterity when compared with the barehand level of dexterity. Fingertip lights were detrimental for all suits, especially for suit C, and it was recommended that placement of the lights be improved. The concept of adding fingernails to glove fingers appears worthwhile and should receive more development.

Functional reach. - None of the suits was rated as meeting all requirements because the operational-reach requirements for all possible contingencies, both intravehicular and extravehicular, cannot be defined. For the vented condition, there was little difference among the suits. For the pressurized condition, suit A placed first, suit B second, and suit C third. Careful attention should be given to the design and location of all fittings to prevent pressure points and to insure that they do not contribute to mobility decrement.

The comfort test accounted for 7 percent of the total score for each space suit. The objective of the evaluation was to obtain a measure of suit comfort during various test conditions and to compare the suits on this basis. No special equipment was required for the comfort test because the evaluations were made when the subject carried out the subtests described in preceding sections of this report. The comfort evaluations were primarily subjective, consisting of the subject's responses to comfort questionnaires completed after each of the subtests. Using the rating scale, the test subject was required to rate suit comfort on the basis of overall comfort, thermal comfort, pressure points, and skin irritations (abrasions, rubbing, and pinching, for example). Appendix A contains a copy of the comfort rating form. In addition, the subject's body was examined for pressure-point marks, scratches, blisters, and other indications of discomfort.

Analysis

The ratings on comfort during the subtests were tabulated, and means were computed for each subject. On the basis of these data, suit C was rated first, suit B second, and suit A third.

In addition, each suit was assigned a rating relative to the torque involved in carrying out movements, thus developing a suit comparison based on the subject's perception of the amount of effort required to accomplish desired movements. On the basis of this rating, suit A was ranked as first, suit C as second, and suit B as third.

At the outset, it should be noted that the three space suits were made specifically for the astronaut serving as test subject; consequently, suit-fit should have been optimized. This should also have been the case for the second subject, since he is nearly identical in size to the astronaut. However, the fit of suit B was less than optimal for the astronaut, and suit A was not a perfect fit. Generally speaking, these two suits fit the second subject more adequately. In terms of general suit-fit, suit A seemed best for both subjects, suit C second, and suit B third. While suit-fit was not perfect, test data were not degraded.

Suit B. - The astronaut who served as test subject made the following observations during the fitting of the suit B.

1. First fitting (vented):

Pressure point location	Extent of pressure
Top of each shoulder	Severe
Tip of each thumb	Moderate
Top of head	Moderate
Tight in hips and thighs	Mild
Knees tight when bent	Mild

2. First fitting (pressurized):

Pressure point location	Extent of pressure
Top of each shoulder	Moderate
Each armpit	Severe
Base of each thumb	Moderate
Each hip bone	Severe
Top of head	Moderate

3. Second fitting (vented):

Pressure point location	Extent of pressure
Vent tube pressing against outboard side of left foot	Moderate
Top of each shoulder	Moderate
Top of head	Moderate

4. Second fitting (pressurized):

Pressure point location	Extent of pressure
Both armpits	Severe
Top of each shoulder	Moderate
Top of arch, left foot	Mild
Base of each thumb	Mild
Top of head	Moderate

5. Third fitting:

   a. During vented condition, pressure points on top of each shoulder

   b. During pressurized condition, pressure points in each armpit

   c. Could not straighten up because of insufficient clearance on top and back of head

6. Fourth fitting:

   a. Mild pressure point on top of each shoulder

   b. During fitting under pressurized condition

      (1) Severe pressure point under each armpit, (worse on left)

      (2) Moderate pressure point on top of left foot

      (3) Crotch rides up too high, moderate

Suit C. - The astronaut who served as test subject made the following observations after the fitting of suit C. Observations were made during the vented condition.

Pressure point location	Extent of pressure
Right toe (bumps against end of boot)	Mild

Pressure point location	Extent of pressure
Both knees (bind and rub against suit when sitting)	Mild
Right thigh (urine valve digs into skin, overall thigh circumference marginal)	Moderate
Right-hand multiple gas connector digs into top of hip bone when connecting spacecraft hose	Moderate
Right shoulder (bearing ring digs into top of shoulder, right side only)	Mild
Gloves too tight on fingers, especially middle finger on both hands (caused by insufficient glove length)	Moderate
Helmet pushes down on top of head when standing (more clearance required)	Moderate

Suit A. - The astronaut who served as test subject made the following observations after the fitting of suit A.

1. Gloves a bit unstable

2. Pressure points over thighs (conical portions), pressure starts in back of thighs and works inboard to the front

3. Pressure points on shoulders

4. Tightness around rib cage (when suit was pressurized)

The space suits appeared to fit the second subject better than the astronaut because of a slight difference in torso height between the two subjects. Concerning suit A, the second subject noted the fit as being "OK." For suit C, there were pressure points and skin irritations (ultimately causing a heel blister) on the inside of the ankles and 1 inch below the ankle bone. The second subject had two fittings with suit B; and for this suit, he noted pressure points on the shoulder and elbow of his left arm, a pressure point under the arms, and a pressure point on the arch of the left foot.

Results

Problem areas during the comfort test may be summarized as follows.

Suit B. - The subject noted rather severe pressure points on the shoulders (near the edge), in the armpits, in the groin-crotch area, on the hips and buttocks, and on top of the arches of the feet. Subjects also complained of being hot; and, during the treadmill test, the left foot curled up the inner lining, balling it up under the foot.

Suit C. - Most pressure points were of a minor nature except for a severe pressure point on the pectoral area brought about by the sharp edge of an inside water connector. Areas of minor pressure were on the tops of the feet and where the boots join the convolutes, at the base of the thumb, behind the knee (in the CM couch), on knee caps, under the urine dump valve, and on the left heel (which caused a blister). Generally, the suit was comfortable.

Suit A. - The most severe pressure points were those in the crotch area, armpits and forward part of the armpits, thigh area from back and then frontward and upward to the crotch and groin, and in the pectoral area where one subject received a blood blister during strenuous motion. Other problem areas included skin irritation on the top of the hand, pressure points in the wrist area near the thumb, the knees, and in the general area of the thigh.

General discomforts. - Many of the subtests required wearing the LCG, and this resulted in a great deal of discomfort, because the tubes bury deeply into the skin and follow the movement of the skin. Consequently, the subject never escapes these pressure points.

As for donning discomforts and difficulties, the subjects had difficulty in donning all the suits. Suit B was very difficult to don because of the bunching of excess material and vent tubes in both foot endings. There was also some bunching of material in the foot endings of suit C, and the lower slip ring of this suit seemed somewhat small in diameter. There was difficulty in donning suit A because the zipper was approximately 2 inches too short.

Recommendations

It is recommended that further developmental studies be carried out relative to optimal suit fit and comfort. Pressure points on the hands can be relieved by more work on the gloves, especially at the base of the thumb and on top of the hand where a poorly fabricated vent tube can irritate the skin. The shoulders in suit A should be adjusted to relieve acromial pressure points, and the cables in the crotch area need study in order to relieve severe pressure where the convolute bunches inward. Also, the stepdown cone in the thigh of suit A is too steep and should be changed.

Pressure points caused by sharp edges on the suit hardware can be easily alleviated by removal of the sharp edges. The pressure points in the armpits and pectoral areas should be removed by adjustments to the suit-man interface in these areas. The pressure point and skin irritation on the ankles may be eliminated by redesigning the convolute-boot-foot interface or by making the boot higher in that area. In any case, the good ankle mobility is highly desirable while the skin irritation is not desirable. It appears that the entire area of the suit-comfort and suit-mobility interface needs considerable developmental work. The question is whether loss of comfort is the price one must pay for good mobility.

FIELD MAINTENANCE EVALUATION

This evaluation was conducted as an addendum to the engineering test and was not included in the test suit scores. The objective of the field maintenance evaluation was to determine the number of necessary repairs and the difficulty in making field repairs.

Repairs

During the testing period, the following suit repairs were made by company representatives.

Suit B. - Repairs to suit B were:

1. Lengthened legs 1 inch

2. Restrung for better fit

3. Added lacing tapes to back of suit

4. Repaired zipper leak
5. Replaced compression band alinement pin four times
6. Fastened vent tube to neck ring
7. Repaired leak in bladder
8. Recemented restraint material to left-wrist disconnect
9. Repaired LCG foot ending

Suit C. - Repairs to suit C were:

1. Replaced broken shoulder slip ring
2. Repaired extravehicular visors
3. Retied lacing cord knot at slip ring
4. Recemented vent liner in glove
5. Replaced gusset zippers on both boots
6. Recemented fingertip lights
7. Recemented stiffeners in gusset
8. Shortened vent system
9. Recemented glove fingertip wires
10. Reworked manifold of vent system
11. Replaced latching dog on multigas disconnect

Suit A. - Repairs to suit A were:

1. Repaired vent on helmet ring
2. Repaired restraint layer on both boots
3. Repaired both gloves
4. Lubricated shoulder turn-around cables

5. Repaired right-knee bellows

6. Repositioned spring end in holddown buckle

7. Replaced pressure sealing zipper

Of these repairs, the three major ones were: (1) the legs of suit B were lengthened 1 inch; (2) a broken slip ring was replaced in the shoulder of suit C; and (3) the pressure sealing zipper in suit A was replaced.

Weak Points

During all inspection and testing, the three suits were continually checked for weak and strong points relating to field maintenance.

Suit B weak points were:

1. Hinge point on neck ring
2. Compression-band guide pins
3. Communications carrier
4. Vent connectors in upper-leg area
5. Convolute cords
6. Extravehicular visor attachments
7. Multigas-disconnect latching dogs
8. Outer cover snagged and was torn easily

Suit C weak points were:

1. Slip rings and lacings
2. Helmet locking device
3. Latching device on compression band
4. Gusset foldover
5. Triloc sole inserts

6. Wire inserts in finger area of gloves
7. Compression-band metal too soft
8. Bunching of material in leg areas
9. Palm restraint cover
10. Holddown cable guides on neck ring

Suit A weak points were:

1. Pressure sealing zipper (upper end)
2. Glove bladders
3. Boot restraint cover at instep
4. Helmet too small
5. Crotch cable and sleeves
6. Unprotected bellows joints
7. Mechanical device for holddown strap

Suit Leakage

Suit leakage before and after the test program is shown in the following list.

Space suit	Before	After
Suit B	3200 cc/min	All in excess of 3600 cc/min
Suit C	700 cc/min	
Suit A	3075 cc/min	

Ratings and Recommendations

Based on the rating scale, suit A ranked in first place, and suits B and C had equal scores for second place. Regarding field maintenance, the recommendations are:

1. The comfort liner should be completely removable (zippers or velcro).

2. The torso should have contouring in the waist area.

3. High semirigid boots with ankle convolutes are recommended.

4. A fixed neck ring is recommended.

5. There should be a pressure-sealing zipper in the back area, but it should be offset from the restraint zipper with a spine protector pad.

6. There should be molded foot-endings in a pressure retention bladder with a flocked interior.

7. A twist-to-lock type of multigas disconnect is recommended.

8. There should be a pressure-retention bladder that is completely protected with an outer cover.

9. No lacings should be exposed.

10. The LCG port should be of the single connector type.

RESULTS AND DISCUSSION

The space suit evaluation program consisted of the operational functions test, engineering test, basic functions test, and comfort test.

The operational functions test contained seven subtests in which suit A was rated in first place for a total of six times, and suit C was in first place in one subtest. Rated according to the operational functions test, suit A placed first in all subtests except vision in the LEM. Suit B placed second for a total of four times, and suit C placed third for a total of four times.

The engineering test contained nine subtests in which suit C placed first in six subtests, suit A was first in two subtests, and suit B was first in one subtest.

In the basic functions test, suit A rated in first place for all except one subtest. Suit A rated first in four subtests, and suit B rated first in one subtest.

For the comfort test, suit C was rated first, suit B as second, and suit A as third.

A tabulation of the relative placement of each suit in each category is given in table XXVII. Relative placements are summarized in the following list.

Space suit	Firsts	Seconds	Thirds
Suit B	2	11	9
Suit C	8	6	8
Suit A	12	5	4

Based on overall results of the test program, suit A placed first in the evaluation, suit C was second, and suit B was last.

CONCLUDING REMARKS

The results of the Apollo space suit evaluation study may be summarized as follows.

1. From a total of 66 separate evaluations, the three space suits met or exceeded minimum specification requirements for a total of 16 times; 7 times for suit C, 7 times for suit A, and 2 times for suit B. In the light of this fact, it is suggested that the conclusions and recommendations of this report serve as guidelines to enhance further suit development.

2. The study indicates that it is possible to establish a series of meaningful test situations for space suit evaluation. By combining these test situations with a rating system, it was possible to evaluate each space suit and to evaluate space suit differences.

TABLE XXVII. - APOLLO SUIT EVALUATION PROGRAM: RESULTS AND SUMMARY

Test	Suit C Place	Suit B Place	Suit A Place
Operational functions test			
Reach in the CM	3	2	1
Vision in the CM	2	3	1
Reach in the LEM	3	2	1
Vision in the LEM	1	3	2
Suit adjustments	3	2	1
Operational mobility (LEM and CM)	3	2	1
Physiological tests	2	3	1
Engineering test			
Pressure drop	3	1	2
Leakage	1	3	2
Helmet tests	1	2	3
Component functions	1	2	3
Dimensions	2	3	1
Weight	1	2	3
Preinspection	2	3	1
Proof pressure	1	3	2
Centrifuge	1	2	[b]NA
Basic functions test			
General mobility	2	3	1
X-ray study	3	1	2
Maximum vision	2	3	1
Hand dexterity	3	2	1
Functional reach	3	2	1
Comfort	1	2	3
Field maintenance[a]	2	2	1

[a]Not included in final scoring.

[b]Scored as 0 for computation.

3. Test results indicate the strong and weak points of space suit design. Based on these test results, it is possible to designate the areas needing further improvement.

4. It is recommended that the procedures of this test program be refined to develop an analysis tool which will have significant use for competitive evaluation, for developmental design input, and for decision making of management.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, March 23, 1966

APPENDIX A

RATING FORMS

Two types of rating forms were used in the space suit evaluation. One form was used by the rating team, and the second form was used by the test subject. The test subject evaluated suit comfort for each subtest. Both types of forms are illustrated on the following pages.

(Form used by rating team)

SUIT COMPARISON TEST

RATING FORM

Rater: ____________________ Suit: ____________ ____________

Test: ____________________ Date: ____________ Time: ____________

Sub-test director: ____________________

1. Rate the overall performance of the suit on the following scale (circle one point along the scale):

(0)	(2)	(5)	(10)	(17)
Totally unacceptable	Highly questionable acceptance	Marginal acceptance	Meets all requirements	Superior, exceeds all requirements

2. If there are several items involved, give each item a rating (circle one point along the scale, using the above scale as a guide):

TEST ITEM	RATING
____________________	(0) (2) (5) (10) (17)
____________________	(0) (2) (5) (10) (17)
____________________	(0) (2) (5) (10) (17)
____________________	(0) (2) (5) (10) (17)
____________________	(0) (2) (5) (10) (17)
____________________	(0) (2) (5) (10) (17)
____________________	(0) (2) (5) (10) (17)

3. COMMENTS: (Put comments on back of this sheet)

(Form used by test subject to rate suit comfort)

SUIT COMPARISON TEST

COMFORT RATING

Subject (Rater): ________ Suit: ________

Test: ________ Date: ________

Time: From ________ To ________ Sub-test director: ________

Rate the comfort of the suit for this test on the following items, using this scale:

(0)	(2)	(5)	(10)	(17)
Totally unacceptable	Highly questionable acceptance	Marginal acceptance	Meets all requirements	Superior, exceeds all requirements

Circle one point along the scale, using the above guide:

1. Overall comfort
   a. Vent condition: (0) (2) (5) (10) (17)
   b. Pressurized: (0) (2) (5) (10) (17)
2. Thermal comfort
   a. Vent condition: (0) (2) (5) (10) (17)
   b. Pressurized: (0) (2) (5) (10) (17)
3. Pressure points
   a. Vent condition: (0) (2) (5) (10) (17)
   b. Pressurized: (0) (2) (5) (10) (17)
4. Skin irritation (abrasions, rubbing, pinching)
   a. Vent condition: (0) (2) (5) (10) (17)
   b. Pressurized: (0) (2) (5) (10) (17)

COMMENTS: Describe any problems on the back of this sheet.

APPENDIX B

COMPONENT FUNCTIONS SUBTEST

INTRODUCTION

This subtest contains ten subsections which evaluate the gas connectors, wrist disconnects, suit entry, neck ring, pressure gage, relief valve, water connector, PGA gloves, extravehicular visors, and electrical harness. Areas of analysis included feasibility of operation, operating characteristics (such as torque and force), specification requirements, and efficacy of design and operation.

GAS CONNECTORS

This portion of the evaluation investigated the following areas pertinent to the mission requirements of the gas connector.

1. Connect force
2. Disconnect force
3. Redundant locking
4. Diverter valve
5. Protection against accidental, inadvertent, or improper actuation
6. 360° swiveling capability
7. Automatic locking feature

Procedure

The connecting and disconnecting forces of the gas connector were measured with a spring scale. It was also noted whether or not the connector would swivel-lock automatically and redundantly, whether it included diverter valves, and whether it was foolproof.

Analysis

Suit A was given a minimum rating because the contractor submitted Gemini-type gas connectors (suits B and C contractors submitted multiple gas connectors). Suit A connectors performed as designed, but they did not meet the stringent requirements that the gas connectors of suit B and suit C were able to meet.

Suit C was given a marginal rating because of the high forces required for connect and disconnect, the lack of an automatic locking feature, and the high torque required to rotate the male half when connected.

Suit B was given a rating slightly less than completely acceptable because the male half had a tendency to lock prematurely (that is, before both halves were engaged). The connector also had other minor deficiencies.

Conclusion

Of the three arrangements, the connector of suit B met the requirements best. It is recommended that this gas connector, with appropriate modifications, be used in future suits.

WRIST DISCONNECTS

The objective of this area of component functions was to investigate the positive and negative features of each type of wrist disconnect.

Analysis

The wrist disconnects of suit B incorporated a wrist vent valve to prevent the suit from losing pressure in the event of glove failure; however, there was no wrist cuff for this purpose, so the valve was meaningless. The vent valve was not tested. There was difficulty in passing the hand through the suit half of the disconnect. The wrist connector of suit B also contained a dust seal. This seal significantly increased the bearing torque, and proof of its effectiveness was not demonstrated. The connector of suit B was susceptible to being misalined and rendered inoperative. When this occurred, the Delrin paws were sheared.

The connectors of suit C used a flange-mounted glove-half connector which provided certain maintenance advantages. The flange projected outward from the glove about $\frac{1}{8}$ inch. It should be noted that this projection is not greater than that of all the suit-half wrist disconnects. The color of the wrist disconnects for suit C was the same, which eliminated the match-color aids when donning the gloves. However, there was no apparent increase in glove-donning time which could be attributed to this factor. The connectors of suit C did not provide a wrist cuff vent duct seal, or a bearing seal. The bearing operated roughly, due partially to the presence of dirt and the galling of parts. The steel paws of suit C withstood the wear imposed upon them.

Suit A provided the Gemini-type design. The lock and unlock indicators could not be read when the upper-arm bearing was placed near one of its stops. Paws of suit A were Delrin.

Conclusion

From a functional and operational standpoint, it is concluded that the disconnects are not adequate for the mission. The steel paws in the connector of suit C were superior to the Delrin paws of suits A and B. It is suggested that the design requirements and rationale be studied and modified to enable the connector to be simplified to the point of acceptance. It is recommended that paws be eliminated from the design and that they be replaced by a simpler mechanism.

SUIT ENTRY

This phase of the component functions evaluation consisted of investigating the design of the suit entry.

Procedure

Rating forms were completed by an evaluation team. The design-area scores were weighted, and their sum averaged. This average indicated the final score. The design areas evaluated included reliability, susceptibility to damage, weight, performance, simplicity, suit reliability, and materials.

Analysis

None of the three suit entries was acceptable. The alinement pins of suit B bent each time the suit was closed, and the zipper closure leaked excessively. The gusset closure of suit C could not be operated by the suited subject. The zippers of suit A were very difficult to reach, and they caught in the constant wear garment several times during donning.

Although the suit A entry was considered superior to the suit B and suit C entries, it was far from acceptable because it leaked excessively. Suit entries should be considered one of the main areas of development.

Conclusion

It is suggested that a gusset closure be used on the Apollo suit because of its greater simplicity and reliability when compared with a zipper closure.

NECK RING

This phase of the component functions evaluation consisted of rating the design of the neck ring assembly.

Procedure

An evaluation team completed the rating forms after an explanation was given for each analysis area. These areas included reliability, susceptibility to damage, weight, volume, material, simplicity, and suit reliability. After the area scores were weighted, the final score was indicated by averages of these weighted area scores.

Analysis

The neck ring designs were conceptually similar in all three suits. The neck rings of suits A and C were difficult to operate due to tolerance problems; whereas, the neck ring of suit B had no positioning feature, which degraded the subject's donning capability. The redundant locks on the neck rings of all three suits were not acceptable.

Conclusion

While the neck ring of suit C was considered superior to the neck rings of suits A and B, the difference was small. Because of the similarity among the three concepts, a first-place position could not be determined.

PRESSURE GAGE

The objective of this test was to determine the adequacy of the pressure gages used on the three suits and to rate each gage with respect to operational characteristics, ability to meet specification requirements, and overall feasibility.

Procedure

The pressure gages were tested as follows:

1. Measure operating pressure for accuracy
2. Note fail-open or fail-closed position
3. Note areas susceptible to damage (for example, cover and attachment)
4. Determine simplicity of design
5. Determine effects on suit reliability
6. Evaluate readability
7. Determine effectiveness of gage to read pressure decay
8. Evaluate scale readings in terms of number of increments
9. Evaluate ability to read gage in pressurized and unpressurized condition
10. Determine if gage is shockproof
11. Determine if gage is field replaceable

Analysis

Final ratings indicated little difference between the pressure gages of suits A and B, which rated first and second respectively. However, both rated higher than the pressure gage of suit C. Compared with suit B, the gage of suit A rated better in only one area, which was the location of the gage in the pressurized suit condition. However, it should be noted that the gages of suits A and B are indentical and are made by the same company. Although the gage of suit C is of identical internal construction and also made by the same company, the faceplate is different in that the gage of suit C ranges from 10 to 2 psia, and the gages of the other two suits range from 6 to 2 psia. The faceplates of the gages on suits B and A are better designed in that the cabin and lunar operating pressures are color-coded "green" and may be read from 5.2 to 4.8 psia and 3.7 to 3.3 psia respectively (with an acceptable degree of accuracy).

For all three gages, an internal rupture of the diaphragm would not cause a suit leakage but would make the gage inoperative. However, since the clearface is mounted with a screw-on cover and a seal on either side of the face, a leak could occur here. Also, if the face were ruptured, a suit leakage would exist because the interior of the gage responds directly to suit pressure, and the internal pressure of the diaphragm is the reference pressure. None of the gages is accurate enough to read pressure decay in order to determine suit leakage prior to lunar activity. All gages are field replaceable; and, of the three, the gage of suit C is most easily field replaceable. However, since the gage of suit C is not attached directly to the suit but by a 3-inch-long pressure tube, it may become dislocated beneath the thermal meteoroid garment and thus reduce the suit reliability, for a ruptured tube will cause an excessive suit leakage.

Conclusion

The gages of suits A and B would suffice for the Apollo mission, except for suit checkout. The location of the gage on the lower left arm is satisfactory on suit A, but the gage must be moved inboard approximately 1 inch on suit B. The mounting technique used on suit C is not acceptable from a reliability and readability standpoint. Also, the faceplate scale of the gage on suit C is not arranged correctly for the Apollo mission.

In order to obtain maximum mission usage, it is recommended that the crewmember who remains aboard the command module in lunar orbit use the magnetic gage similar to the one used on suit B (psia gage). The other two crewmembers would then use a psig gage designed not to leak in the event of damage to the case of the gage. The psig gage would act as a psia gage on the lunar surface and would also be able to read suit leakage for the checkout operation. The internal construction of the gage should be checked very carefully for shock and vibration. The internal design of the gage appears too delicate for its intended usage.

RELIEF VALVE

The objective of this test was to determine the operating characteristics, to evaluate the basic design approach for each pressure relief valve on the three suits, and to rate these according to specification requirements.

Procedure

The relief valves were tested as follows:

1. Measure operating pressures and flow

    a. Opening pressure

    b. Reseat pressure

    c. Flow at full-open condition

2. Note fail-open or fail-closed position

3. Note areas susceptible to damage

4. Evaluate simplicity of design

5. Note possibility of failure caused by contamination holding relief valve in closed position

6. Evaluate feasibility of manual override

7. Evaluate effects on suit reliability

8. Determine if relief valve is field replaceable

Analysis

The valves on suits B and C are slow-opening while the valve on suit A is a snap-open. The valve on suit B opens at the specified pressure of 4.30 psig. The full-open flow is approximately 80 standard liters per minute (slpm) at a pressure of 5.5 psig. This flow is fairly close to the 3.25 pounds per hour as specified. The valve reseats at 4.1 psig which is below the 4.3 psig specification requirement.

The valve on suit C operates in approximately the same manner as that on suit B but at a slightly higher pressure. The valve cracks open at 4.62 psig and reseats at 4.53 psig. Flow at full-open condition is 60 slpm and at a pressure of 5.75 psig. The valve of suit A, being a snap-open-type valve, operates in the following manner:

1. Crack open - 5.70 psig

2. Pops open - 6.06 psig

3. Pops closed - 5.43 psig

4. Reseats - 5.35 psig

5. Flow at full-open - 13.8 scfm at 6.06 psig

All valves, being spring loaded against the higher internal suit pressure, will fail in the full-open position.

The valve of suit A is not protected from external contamination; whereas, the valves of suits B and C are protected by being under the cover layer. This protection concept is very satisfactory from all operational standpoints and makes the valves of suits B and C preferable. More components are used in the control for the suit B, making it as a consequence not as simple in design. The three valves presented here are not field replaceable, but this is not a specification requirement at this time. After evaluation of the items discussed above, suit C was rated in first place, suit B in second, and suit A in third.

Conclusion

The above evaluation leads to the following conclusions.

1. In operating characteristics, the valve of suit C is slightly superior to that of suit B and highly superior to the relief valve of suit A.

2. All valves fail in the fail-open position.

3. The valves of suits B and C are less likely to be damaged than is the valve of suit A.

4. The valves of suits A and C are superior in simplicity of design.

5. Valves of suits B and C are far superior to that of suit A in the area of external contamination.

6. The manual override feasibility is not discussed here because it was not presented on any of the valves. (However, it should be noted that a feasibility study is being carried out on the manual override concept.)

7. Suit reliability was not degraded appreciably by any of the valves.

The above evaluation leads to the following recommendations.

1. Future valves should be of the slow-opening type in order to prevent excessive cycling of the suit and valve.

2. A design should be investigated which would prevent the valve from failing to the open position (fails-open).

3. Both internal and external contamination protection should be provided for the valve.

WATER CONNECTOR

The objective of this test was to evaluate the areas of connect force, disconnect force, redundant locking, safety interlock, ease of connect and disconnect, and connector handles.

Procedure

The connecting and disconnecting forces of the water connector were measured with a spring scale. Also, the ease with which this task was accomplished was rated subjectively.

Analysis

Based on this evaluation, suit B rated first, suit C second, and suit A third. Suit A was given a zero on this test because the contractor submitted no water connector for evaluation (mockups only).

The water connector of suit C was rated as only marginally acceptable, owing primarily to a high connecting force and the lack of a safety interlock (this lock prevents the removal of the external portable-life-support-system connector half when the internal connector half [LCG] is not connected). The lack of gripping provisions on the male halves also reduced the score. The water connector of suit B was rated slightly less than completely acceptable due to the lack of gripping provisions on the male halves.

Conclusion

The design of the water connector on suit B, with certain minor modifications, is recommended for use on future suits.

GLOVES OF PRESSURE GARMENT ASSEMBLY

The objective of this evaluation was to determine the adequacy of the PGA gloves. Analysis areas included an evaluation of the feasibility of operation, operating characteristics, specification requirements, and efficacy of operation.

Procedure

This evaluation was divided into two parts. Part 1, which was both objective and subjective, evaluated the PGA gloves in terms of long-term comfort, proper ventilation, dexterity and tactility, fingertip lighting, ease of donning and doffing, material coating, conformity to hand, weight, stowage volume, susceptibility to damage, and leakage. All these evaluations were subjective except the objective evaluations for weight, volume, and leakage. Part 2 of the evaluation was wholly subjective and consisted of the test subject's observations.

Analysis (Part 1)

In Part 1 of the evaluation, suit C rated first, suit B second, and suit A third. The subjective sections of this test were divided into two sections, pressurized and unpressurized. In the unpressurized mode, the gloves of suit B were considered marginally acceptable from a long-term comfort standpoint. During donning and doffing, chafing on the lower wrist-hand area was experienced to a minor degree. Gloves of suit B had no fingertip lights and were considered marginally acceptable in the material coating area. Questionable acceptance was granted for ventilation in the gloves of suit B.

Unpressurized, the gloves of suit A exhibited pressure points on the back of the hand at the outside second joint between the thumb and index finger. These pressure points would detract from performance in long-term comfort considerations. For gloves of suit A, marginal acceptance was granted in the areas of donning and doffing and in the area of susceptibility to damage.

In the unpressurized test, the gloves of suit C exhibited acceptable characteristics from a long-term comfort standpoint and were easily donned and doffed. Marginal acceptance was given for the fingertip lights because the lights require more recess and because the wires were external and subject to damage.

The pressurized mode of this test was used basically to evaluate leakage. Leakage rates for gloves of suits B and C were generally acceptable while leakage rates for gloves of suit A were far in excess of requirements. High leakage rates for gloves of suit A were attributed to degradation of the bladder of the gloves, due to usage throughout the testing.

Analysis (Part 2)

Comments in this section are based on the test subject's observations, and ratings were based on the following areas.

1. Extent of inadvertent glove movements when the glove was put through the motions of yaw, pitch, and roll.

2. Balance conditions and the amount of force required to move the gloved hand through the motions of yaw, pitch, and roll.

3. Hand tiring in both the vented and pressurized condition.

A single score for all three areas was not derived for this evaluation, but relative positions by area were as follows.

1. Extent of inadvertent glove movements when the glove was put through the motions of yaw, pitch, and roll.

Vented	3.7 psig pressure
Three suits rated as equal	Suit B (first)
	Suit C (second)
	Suit A (third)

2. Balance conditions and the amount of force required to move the gloved hand through the motions of yaw, pitch, and roll.

Vented	3.7 psig pressure
Suits B and C (equal rating for first place)	Suit C (first)
Suit A (second)	Suit B (second)
	Suit A (third)

3. Hand tiring.

Vented	3.7 psig pressure
Three suits rated as equal	Suit A (first)
	Suits B and C (rated equal for second place)

Inadvertent inputs. - For the gloves of suit C in the pressurized condition, inadvertent inputs were induced during the pitch down, left roll, and right roll movements. The gloves of suit A exhibited extremely unstable characteristics during the yaw movement. The gloves of suit B had good balance characteristics and had no inadvertent inputs.

Balance conditions and amount of force required. - In the vented condition, gloves of suits B and C had good balance characteristics, while the gloves of suit A required force for the transition between pitch and yaw. In the pressurized condition, gloves of suits B and C showed that light force was required to control roll movements, while forces were medium for the pitch and yaw modes. Gloves of suit A required light force in yaw and heavy force in pitch.

Hand tiring. - All gloves appeared satisfactory in the vented condition. While using the gloves of suits B and C in the pressurized condition, tiring of the forearm was noticed, and this was believed to be due to the pressure lines across the base of the thumb and fingers. From this standpoint, the gloves of suit A were considered acceptable, although upper-arm tiring was noted. When the palm flexes, the gloves of suits B and C do not allow normal movement at the palm breakpoint. This condition was attributed to the location of the gloves' palm restraint.

Conclusion

There were no distinct advantages for any of the gloves, and none of the gloves was considered as having fully met mission requirements. Under these conditions, the evaluation leads to the following recommendations.

1. There should be further development in determining the location of palm restraints.

2. Since inadvertent inputs to the controller cannot be tolerated, it is recommended that the wrist-joint concept of suit B be improved and utilized in the glove design.

3. There should be additional design development to reduce pressure points and improve long duration comfort.

EXTRAVEHICULAR VISOR ASSEMBLY

This phase of the component functions evaluation consisted of investigating the design of the extravehicular visor assembly.

Procedure

Rating forms were completed by the evaluation team after an explanation of the analysis sections. The design area scores were weighted, and their sum averaged. This average indicated the final score. The analysis sections were reliability, susceptibility to damage, weight, simplicity, materials, and suit reliability.

Analysis

Final ratings ranked the extravehicular visor of suit C in first place, suit A in second, and suit B in third.

Concerning the extravehicular visor of suit B, the misalinement of the visor assembly prevented its attachment to the helmet. Fabrication was excellent for the extravehicular visor of suit C. Basic concepts of the visor assembly were almost identical for suits A and C.

Conclusion

Based on this evaluation, it is evident that the concept of the extravehicular visor of suits A and C should be followed in future suit design. Fabrication of this assembly has best been shown by the visor assembly of suit C.

SUIT ELECTRICAL HARNESS

The objective of this evaluation was to determine the adequacy of the suit electrical harness. This evaluation concerned feasibility of operation, operating characteristics, specification requirements, and efficacy of operation.

Procedure

The suit electrical harness was evaluated as follows.

1. Examine harness material
2. Determine if proper connectors were used
3. Examine and determine adequacy of installation in suit
4. Determine conformance with low-profile requirement
5. Determine adequacy of location
6. Determine acceptability of lead routing
7. Determine adequacy of effecting connection

Analysis

Evaluation of the suit electrical harness placed suit B in first place, suit C in second, and suit A in third. In this group of ratings, there was little difference between suits B and C, but a great deal of difference between suit A and the other two suits. Material ratings for all harnesses were given a zero. The harness of suit A used materials not acceptable for production, and the harnesses of suits B and C used silicon rubber.

Suits B and C used connectors specified by NASA, while suit A did not. The harness installation of suit C did not utilize encased harness leads for controlled routing, and the suit connector was located in a poorly chosen area.

As a result of the evaluation, it is recommended that the acceptability of silicon rubber insulation be determined. The harness installation routing techniques employed in suit B should be used in the Apollo Block II suit. The location of the suit-mounted connector should be in an area similar to that of either suit A or suit B.

APPENDIX C

REACH-MEASUREMENT GRAPHS

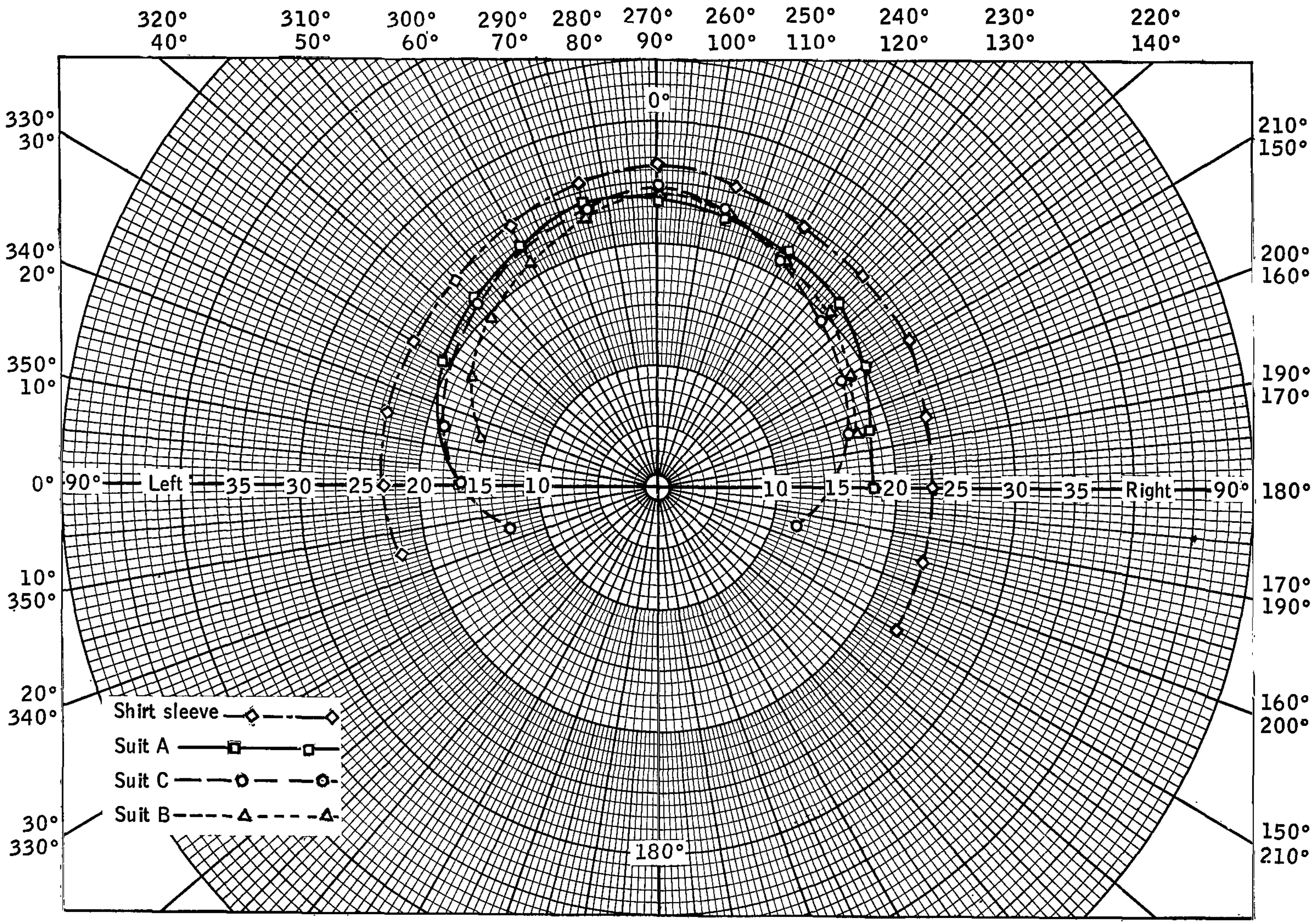

Figure C-1. - Reach measurement, 0° horizontal, vented.

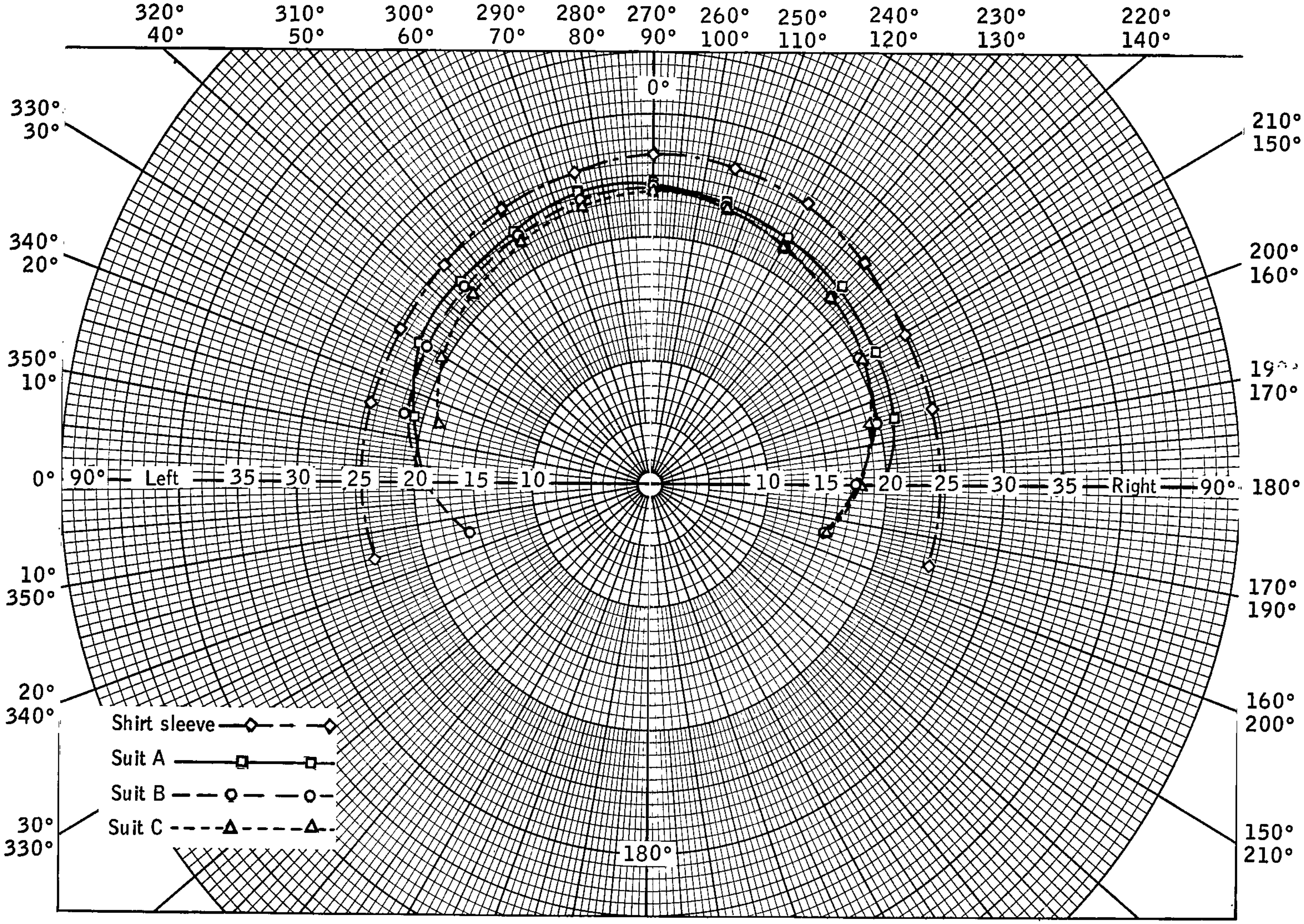

Figure C-2. - Reach measurement, 15° horizontal, vented.

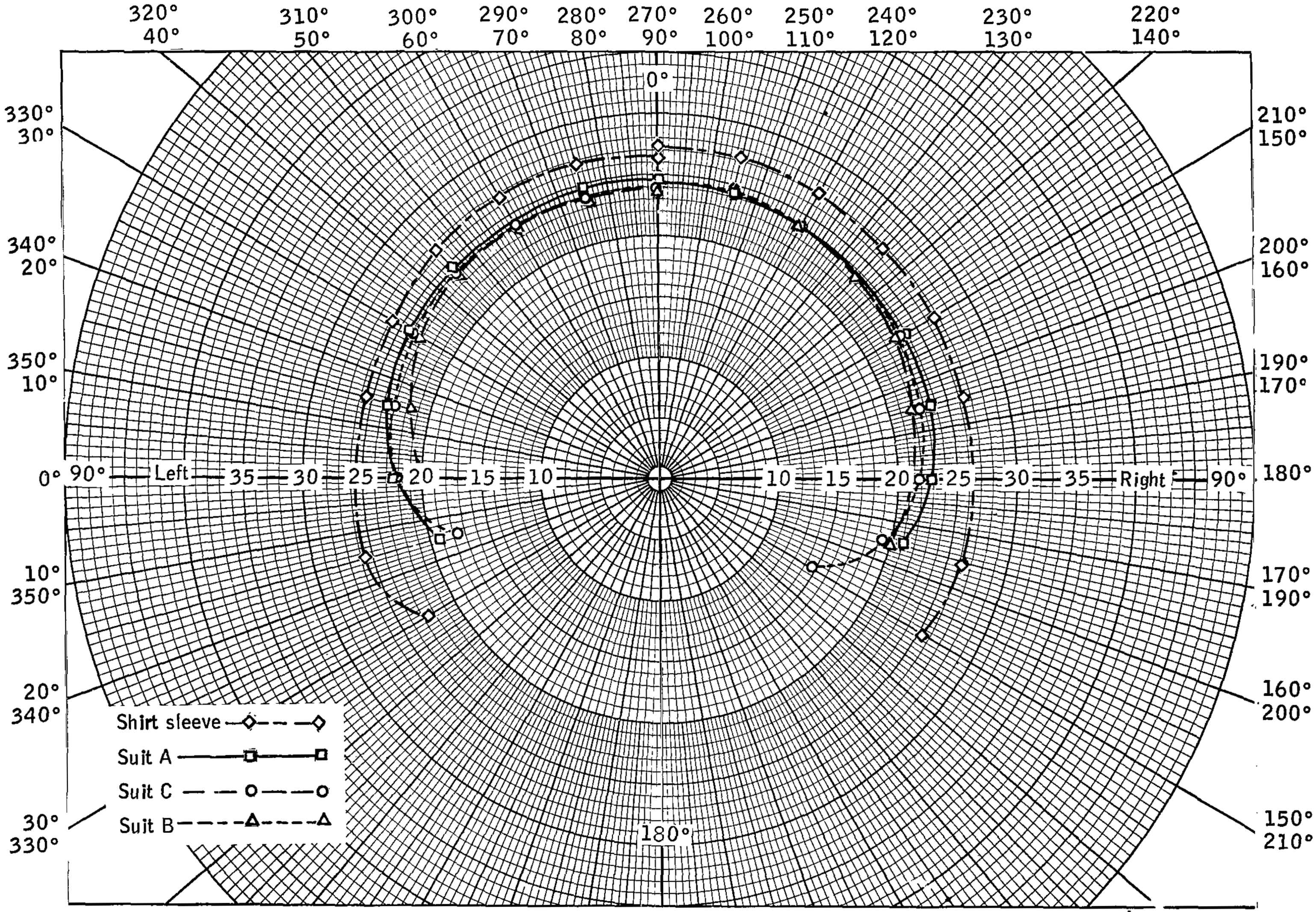

Figure C-3. - Reach measurement, 30° horizontal, vented.

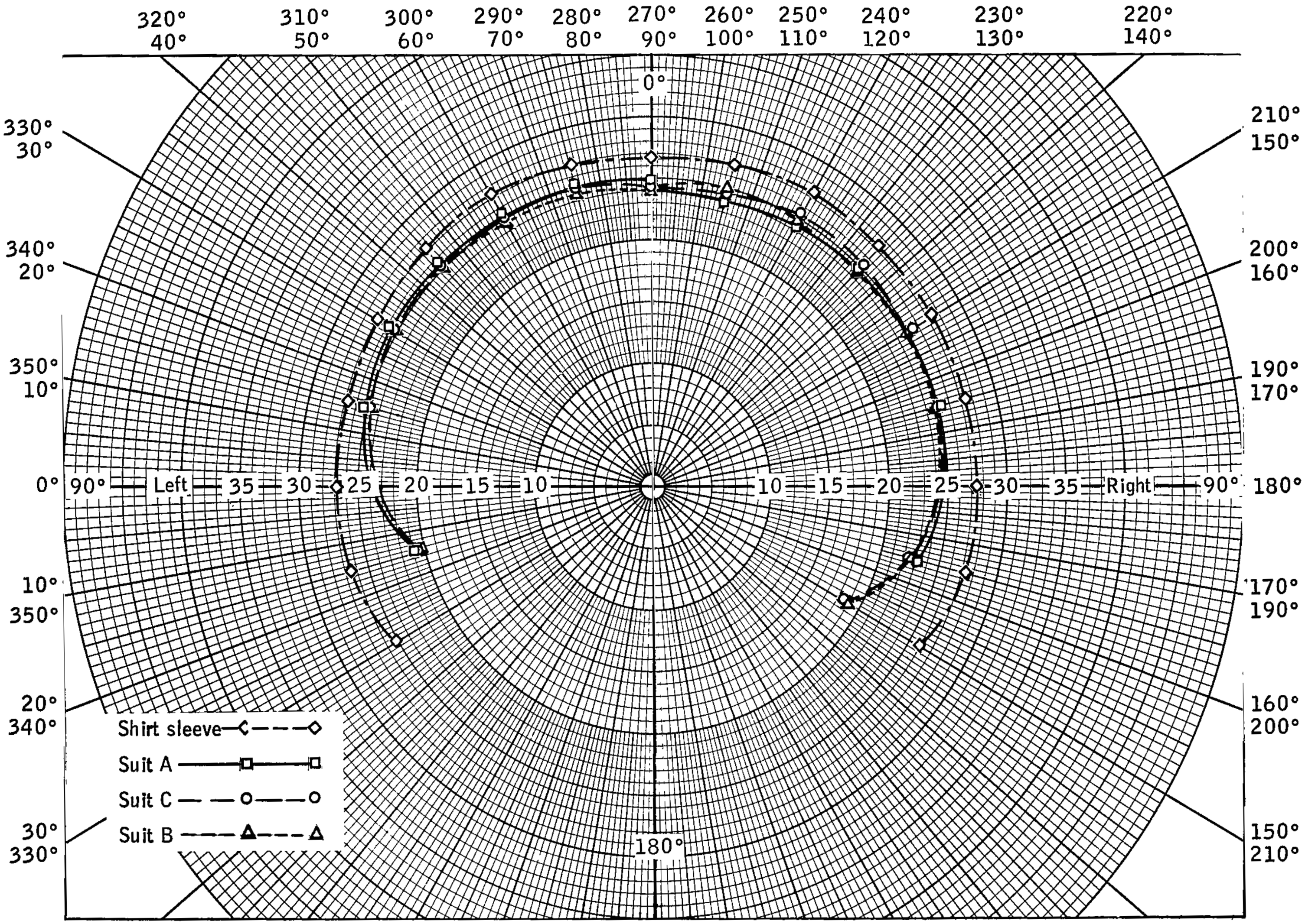

Figure C-4. - Reach measurement, 45° horizontal, vented.

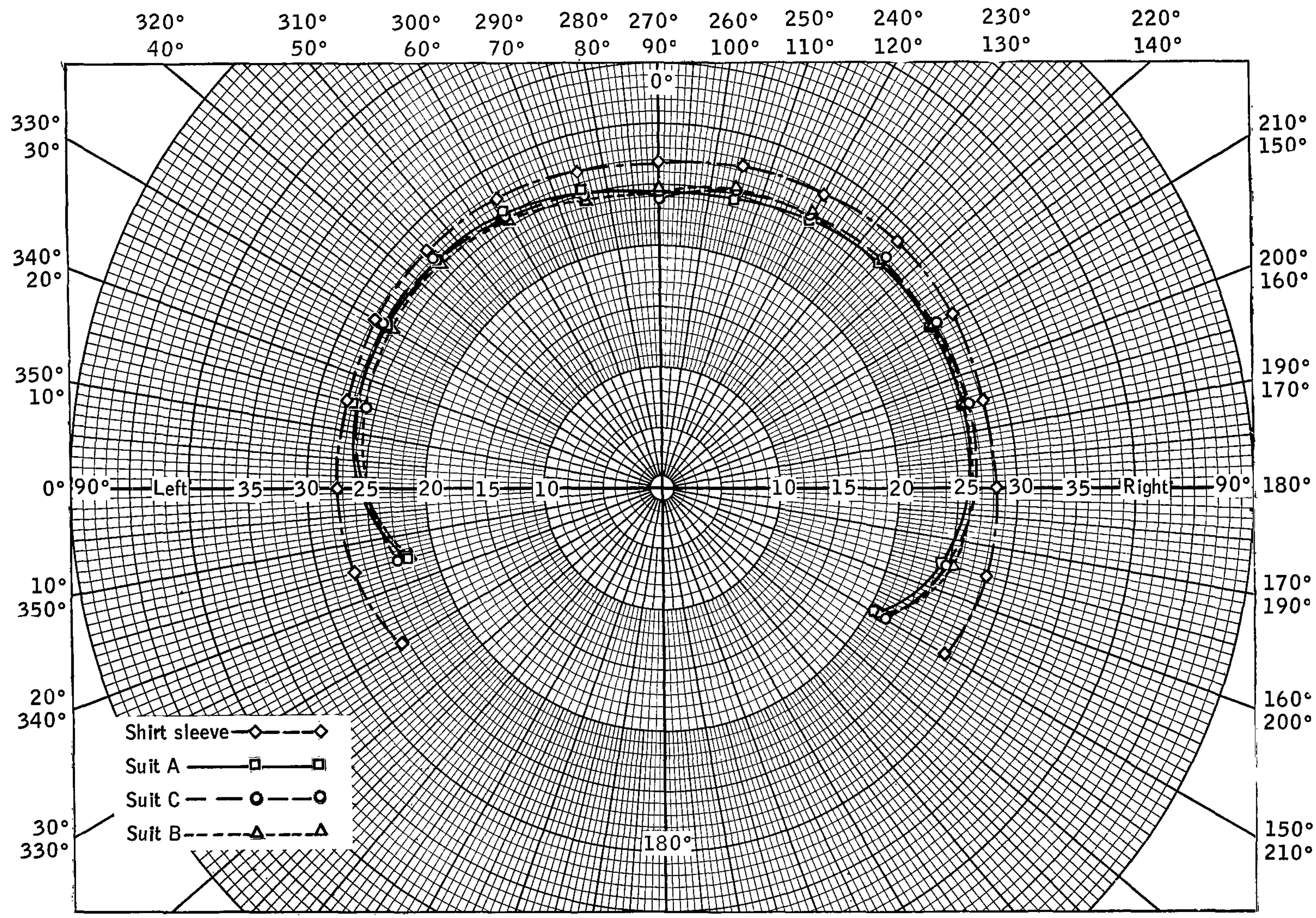

Figure C-5. - Reach measurement, 60° horizontal, vented.

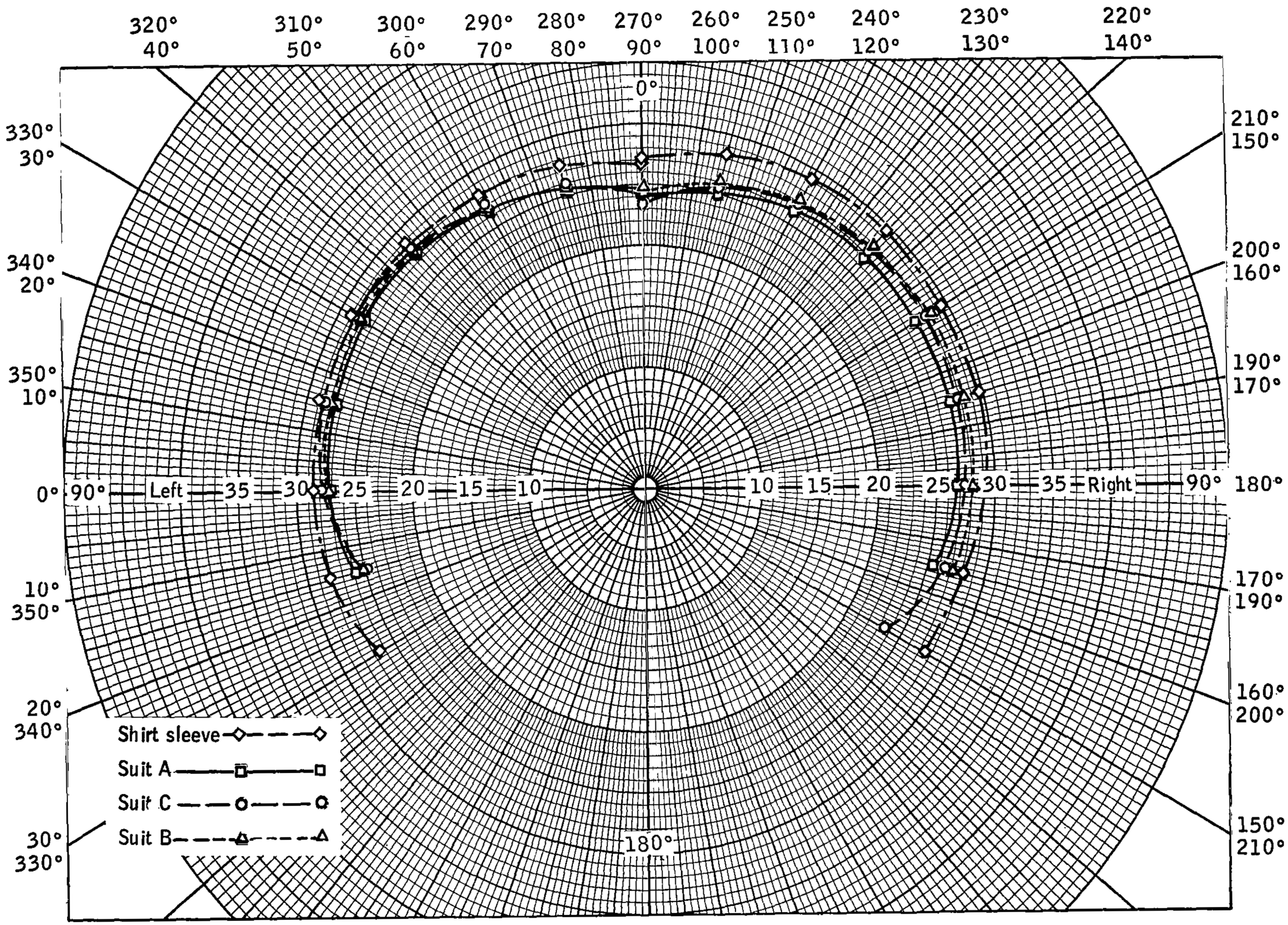

Figure C-6. - Reach measurement, 75° horizontal, vented.

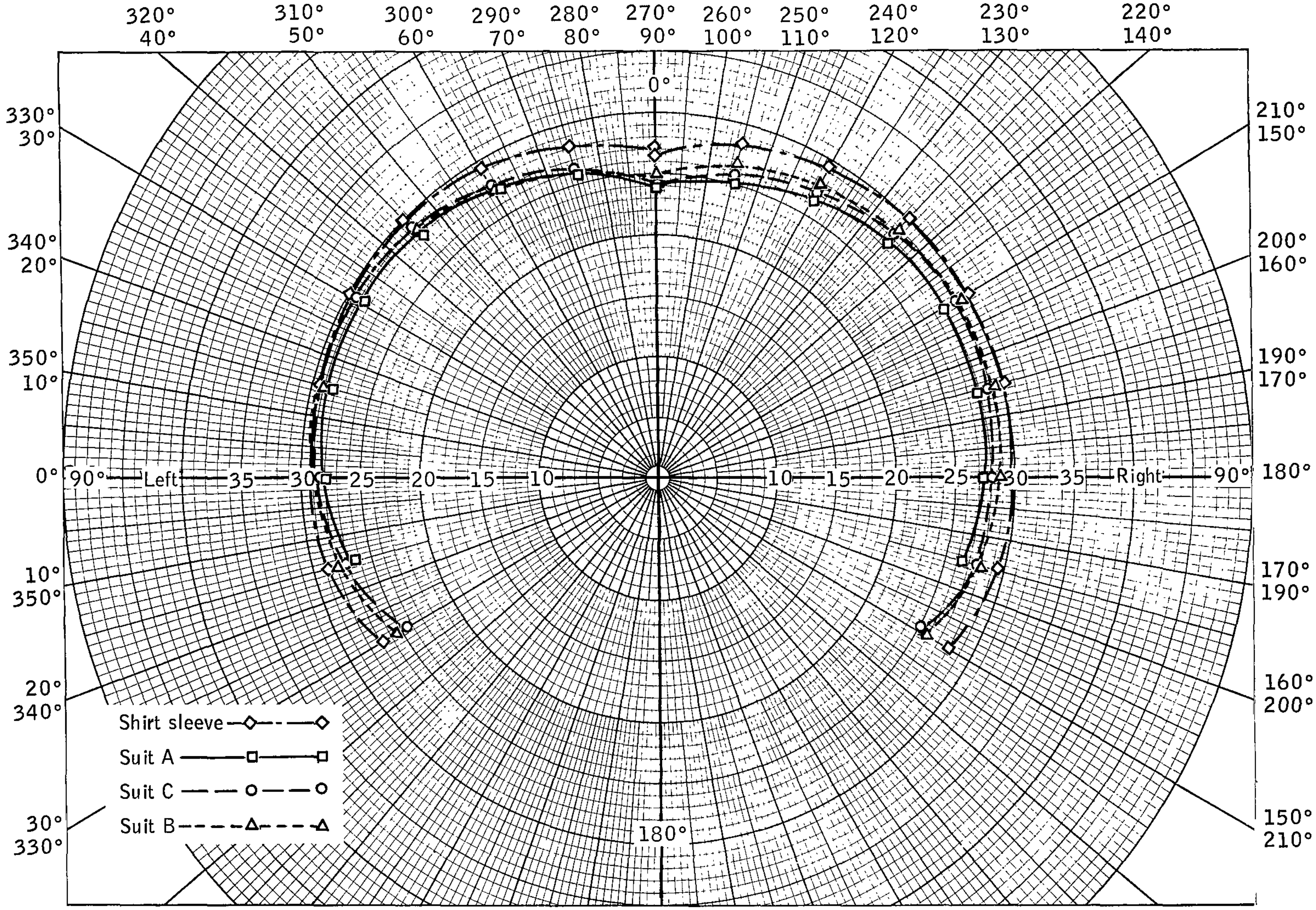

Figure C-7. - Reach measurement, 90° horizontal, vented.

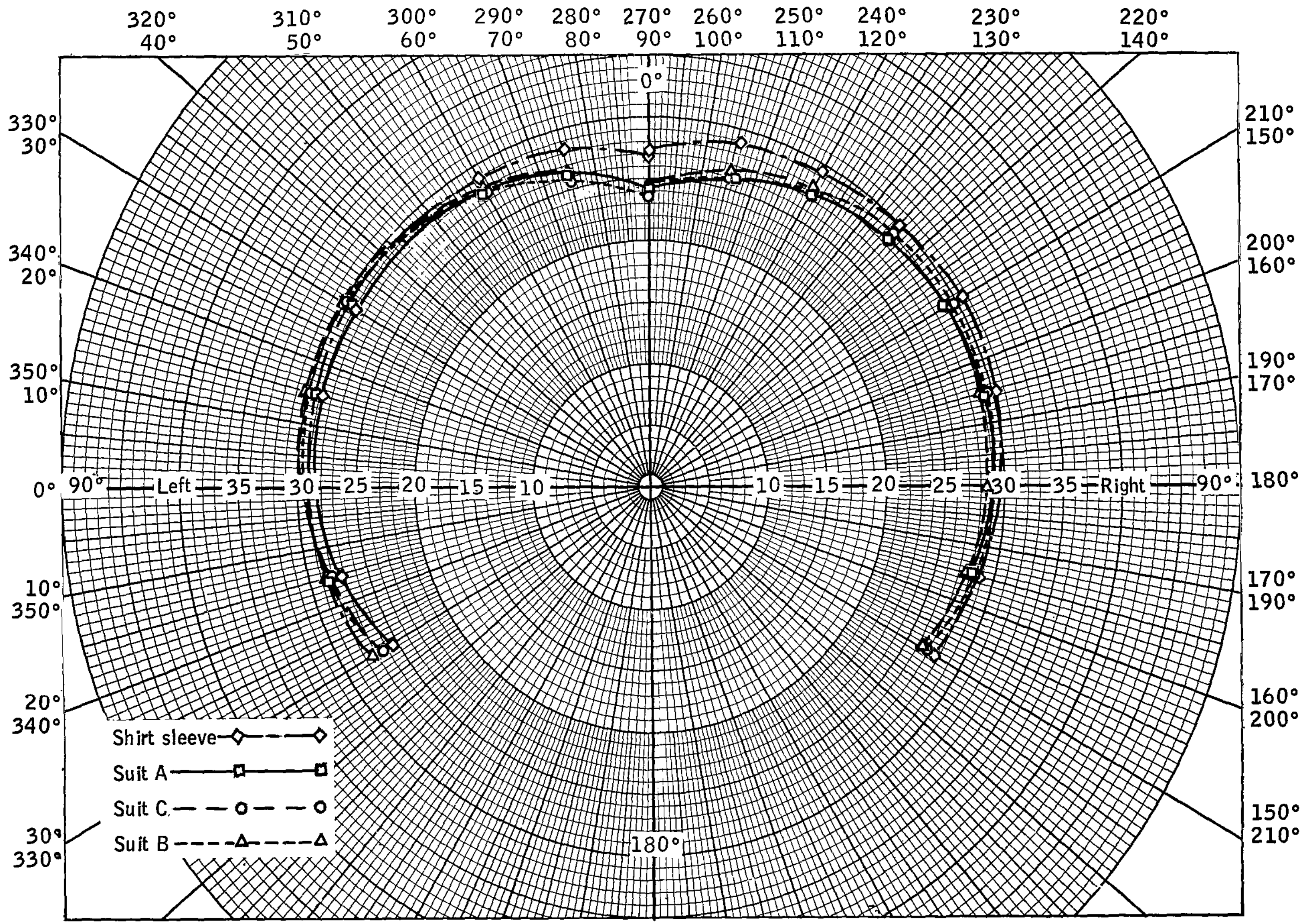

Figure C-8. - Reach measurement, 120° horizontal, vented.

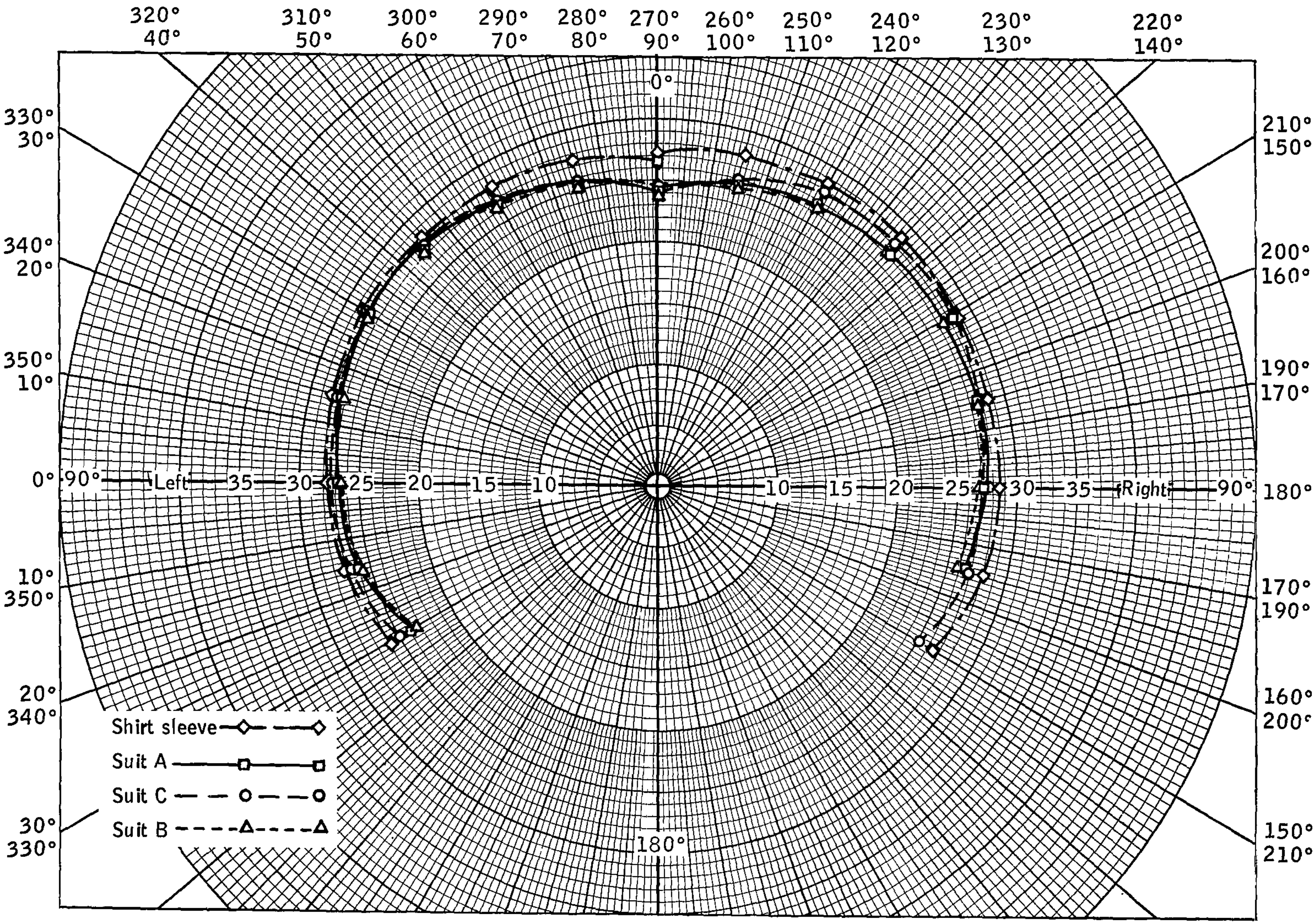

Figure C-9. - Reach measurement, 150° horizontal, vented.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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